

X-644-71-483

NASA TM-X-65939

THE GEOLOGIC EVOLUTION OF THE MOON* (Revised Version)

PAUL D. LOWMAN, JR.

(NASA-TM-X-65939) THE GEOLOGIC EVOLUTION
OF THE MOON (NASA) 67 p HC \$5.50

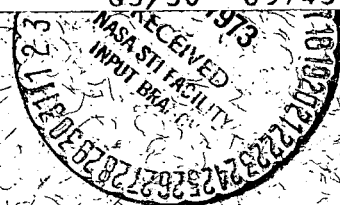
N73-22777

CSCL 03B

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OCTOBER 1971



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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

*Published, Journal of Geology, March, 1972, V. 80, No. 2, P. 125-166.

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ABSTRACT

This paper is a synthesis of pre- and post-Apollo 11 studies to produce an outline of the moon's geologic evolution from three lines of evidence: (1) relative ages of lunar landforms and rock types, (2) absolute ages of returned lunar samples, and (3) petrography, chemistry, and isotopic ratios of lunar rocks and soils. It is assumed that the ray craters, circular mare basins, and most intermediate circular landforms are primarily of impact origin, although many other landforms are volcanic or of hybrid origin. The moon's evolution is divided into four main stages, each including several distinct but overlapping events or processes: Stage I (4.7 billion years ago) — Origin of moon by unknown means, followed immediately by heating of outer 500 km to at least 1000° C; Stage II (4.6 to 3.7 b.y. before present) — First differentiation to form highland crust, by eruption of high-alumina basaltic magma and minor quantities of differentiation products such as anorthosite and felsite; infall of small circum-terrestrial bodies to form old highland craters; formation of circular mare basins by infall of large circum-terrestrial bodies; formation of Archimedes-type craters; highland vulcanism; Stage III (3.7 to 3.2 b.y. before present) — Second differentiation of moon, by generation and eruption of iron-rich basaltic magmas to form maria; Stage IV (3.2 b.y. ago to present) — Sporadic impacts by asteroid belt meteoroids and comet nuclei to form ray craters; local vulcanism and gas venting from deep sources; minor faulting; continual slow landscape degradation by small impacts and other agents. The moon now appears relatively cold and rigid to depths of about 500 kilometers. Major unsolved problems include the composition and origin of the highland crust, the role of vulcanism in formation of ray craters, the nature of the lunar interior, the cause of assymetric mare distribution, and the relation of the moon to the earth.

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THE GEOLOGIC EVOLUTION OF THE MOON

INTRODUCTION

The landing of the spacecraft "Eagle" on the moon in 1969 (Figure 1) was the beginning of first-hand lunar exploration, but it was also the culmination of many years of earth-bound study. The massive flood of new information from the returned lunar samples has understandably overshadowed the pre-Apollo geologic investigations. But much of the earlier work has stood the test of manned lunar exploration, and when integrated with the new knowledge, permits us to construct a surprisingly detailed history of the moon's geologic evolution. The purpose of this paper is to present such a history, based on three main lines of evidence:

- (1) relative ages of major landforms and rock types
- (2) absolute ages of returned lunar samples
- (3) chemistry and petrography of returned samples.

This reconstruction of the moon's geologic history, an earlier version of which was presented in 1970 (Lowman, 1970), is but the latest of several, only a few of which can be mentioned here. Geologically, the work of Shoemaker and Hackman (1962) is the most important; working only with low-resolution telescopic photographs and visual observations, they constructed a lunar stratigraphic time scale from fundamental geologic principles such as superposition. Their work formed the basis for the USGS-NASA 1:1,000,000 scale geologic mapping program, which has culminated in the geologic map of the entire front side of the moon (Wilhelms and McCauley, 1971).

Other noteworthy pre-Apollo reconstructions of the moon's history include that of Baldwin (1963), many aspects of which have been verified by manned lunar landings. For example, Baldwin deduced the extremely basic composition of the mare lavas from their flat topography and scarcity of flow fronts. Khabakov (*in* Markov, 1962) presented a similar though more general reconstruction, although unlike Baldwin, he assumed most of the lunar craters and mare basins to be of volcanic origin. Fielder (1965) likewise favored an internal origin for most lunar landforms, and proposed a lunar time scale in which the maria were a few hundred million years old — an age now known to be too low. Hartman (1964) developed a simplified scheme of the moon's evolution, assuming intense impact cratering, with a time scale that has been proven approximately correct.

EVIDENCE BEARING ON THE MOON'S EVOLUTION

This reconstruction of the moon's geologic evolution rests on three main objective bases. The first of these is the relative ages of the main lunar landforms and rock types. The relative ages of the main physiographic provinces (Figure 2) — highlands, mare basins, and maria — are evident from gross morphology and crater populations, regardless of the processes by which each developed. The highlands are heavily cratered and eroded, and hence must be the oldest; the mare basins, incised in the highlands, are younger; and the maria, filling the mare basins and flooding much additional area, are youngest. Superposition relations then permit us to fit the less-prominent features into a chronologic sequence. Craters excavated, by any process, in the maria are clearly post-mare. The rays from craters such as Copernicus (Figure 3) and Tycho (Figure 2) overlie almost all other landforms, and so these craters are the youngest major features. Superposition can be supplemented, as explained by Mutch (1970), by crater counts and albedo measurements to deduce the relative ages of other features. Though subject to resolution limits and to some extent the assumption that most small craters are of impact origin, this system is objective and the maps based on it of permanent value, especially now that they can be supplemented by study of returned samples.

The absolute ages of returned lunar samples form the second line of evidence for the reconstruction presented here. Because they permit us to put numerical values in the stratigraphic time scale, these ages have been among the most important results of lunar sample analysis. (For an excellent review of lunar geochronology, see Wetherill (1971)). Because the maria form a major stratigraphic datum surface, their crystallization ages are of prime importance; fortunately, there is general agreement among the various investigators on these ages. Several independent methods give crystallization ages of about 3.6 billion years for the Apollo 11 Mare Tranquillitatis basalts and about 3.3 billion years for the Apollo 12 basalts from Oceanus Procellarum. A preliminary determination on basalt returned by the Apollo 15 mission from the Palus Putredinus gave 3.27 billion years. These closely similar radiometric ages support the pre-Apollo inference, from crater counts (Baldwin, 1964), that the major maria (or at least their upper flows) were all formed in about the same period of the moon's evolution, although minor post-mare vulcanism of currently unknown age has clearly taken place.

The absolute ages of the regolith samples, although just as important, are more difficult to interpret. The soil and breccias from Apollo 11 and 12 give ages of about 4.6 to 4.7 billion years, despite the fact that they are largely derived from the younger underlying basalts. As explained by Wetherill (1971), this apparent paradox results from dominance of the radiometric ages by minor amounts of exotic material, probably from the highlands, with ages of about 4.6 billion

years. This figure can reasonably be interpreted as the age of the moon, as well as of the highlands. Independent though still tentative confirmation of the great age of the highlands comes from the radiometric results on small individual fragments that are clearly allocthonous. Luny Rock 1, for example, was found to be 4.4 billion years old (Papanastassiou, et al., 1970). A preliminary determination on the anorthosite sample 15415 from Apollo 15 gave an age of 4.15 billion years.

The third line of evidence for this reconstruction is the cumulative results of petrographic, mineralogical, and chemical investigations of returned lunar samples. These investigations, carried out by scores of scientific teams, have been reported in hundreds of papers and several books; especially useful summaries have been compiled by Mason and Melson (1970) and Levinson and Taylor (1971). Analytical techniques and instruments used by unmanned spacecraft, such as Surveyor, and from lunar orbit are described by Adler and Trombka (1970). The results of these various investigations will be summarized only briefly here; they will be referred to further in the discussion of the evolutionary stages.

Laboratory study of mare samples, from Apollo 11, 12, and 15, and from Luna 16, has shown them to be basic and ultrabasic igneous rock (Figures 4 and 5) overlain by several meters of debris (the regolith; Figure 6) formed largely by innumerable impacts of meteorites and secondary ejecta fragments. Minor amounts of meteoritic iron and fragments of stoney meteorites have been found. The mare regolith also contains a small proportion of exotic fragments generally interpreted as impact ejecta from the highlands: high-calcium anorthosite, anorthositic gabbro, and basalt enriched in trace elements (KREEP - an acronym referring to potassium, rare earth elements, and phosphorous).

The mare basalts (to use the generally-accepted though perhaps inappropriate term for these rocks) thus far collected are broadly similar to each other (Table 1) and share certain distinctive differences from terrestrial basalts. Probably the most important of these is the systematic deficiency in relatively volatile elements, such as K, Rb, and H. There is a corresponding enrichment in refractory elements, such as Ti, although the unusually high TiO_2 content of the Apollo 11 rocks has not been found elsewhere. The mare basalts are extremely reduced, reflecting their deficiency in water (Walter, et al., 1971).

Returned highland samples can not so far be easily characterized, partly because only preliminary results of study of the Apollo 14 and 15 samples are available. Material collected from the Fra Mauro formation by the Apollo 14 crew proved to be largely fragmental, the fragments being largely derived from rock types previously encountered: basalts and rocks of anorthositic affinity

Table 1

Lunar Rock Compositions vs. Terrestrial Basalt

	Apollo 11 ¹	Apollo 12 ²	Apollo 14 ³	198 Terrestrial Basalts ⁴
SiO ₂	40.2	39.7	49.4	49.9
TiO ₂	11.4	3.7	1.7	1.4
Al ₂ O ₃	9.9	11.3	16.8	16.0
Fe ₂ O ₃	0.0	—	—	5.4
FeO	18.7	21.3	9.6	6.5
MnO	0.3	0.3	0.2	0.3
MgO	7.3	11.7	10.6	6.3
CaO	11.1	10.7	9.4	9.1
Na ₂ O	0.6	0.5	0.7	3.2
K ₂ O	0.2	0.7	0.8	1.5

1. Average of 13 basaltic (Type A or B) crystalline rocks, ranging from 37.8 to 42.0% SiO₂, from Apollo 11 landing site, reported in Science, V. 167, No. 3918, 1970. Samples averaged, with authors, include: 10044, 10057 (Engel and Engel), 10017-29, 10020-30 (Maxwell, et al.), 10072 (Wiik and Ojanpera), 10003, 10022, 10024, 10047, 10049, 10050, 10058, and 10062 (Rose, et al.). None of the analysts reported significant combined water.
2. Average of 9 crystalline rocks, ranging from 35 to 49% SiO₂, from the Apollo 12 landing site, reported by the Lunar Sample Preliminary Examination Team, Science, V. 167, No. 3923, p. 1325-1339, 1970. Samples averaged include: 12012, 12004, 12015, 12022, 12009, 12065, 12052, 12064, and 12038. The rocks were described by the LSPET as pyroxene-rich peridotites, olivine gabbros, gabbros, troctolites, and similar types. There was no significant water, judging from the sums.
3. Average of 8 fragmental rocks, ranging from 48 to 51% SiO₂, from Apollo 14 landing site and vicinity, reported by LSPET in Apollo 14 Preliminary Science Report, NASA SP-272, 1971. Samples averaged include: 14321, 14; 14321, 9; 14049; 14042; 14301; 14065; 14066; 14305. Two basalts and fines sample 14259 had very similar compositions.
4. Terrestrial basalts compiled by R. A. Daly (1933). Rocks included 161 basalts, 17 olivine diabases, 11 melaphyres, and 9 dolerites.

(a term suggested by Wood, et al., 1971). The abundance of polymict breccias with evidence of shock metamorphism is quite consistent with, though not proving, the impact origin of most small craters and the Imbrium basin (from which the Fra Mauro formation is considered ejecta). The Fra Mauro formation is notably richer in plagioclase than the mare rocks; chemically, it is notable for enrichment in aluminum and especially in trace elements (e.g., Rb, U, Th, K, and Na). There appears to be a close relation between the Fra Mauro and KREEP, tending to support the idea that the latter, though found in the maria, is of highland derivation. Various aspects of highland petrology will be discussed further in relation to the moon's general geology.

In addition to these three major lines of evidence bearing on lunar geology, there is a rapidly-growing body of information from orbital remote sensing and from the ALSEP. The first extensive orbital compositional experiments were carried on Apollo 15, including gamma ray, X-ray, and mass spectrometers. Preliminary analysis of the X-ray fluorescence experiment (Adler, et al., 1971) indicates that the highlands are systematically higher in aluminum than the maria (Figure 7), thus tending to confirm the indirect evidence of feldspathic highlands from previous missions. These results will be discussed in more detail in relation to the origin of the highlands.

The geophysical data from the Apollo 12, 14, and 15 ALSEPs, all of which are still functioning as this is written, are of considerable indirect geologic interest, and will be referred to as necessary.

ORIGIN OF LUNAR LANDFORMS

Before going on to the main outline of lunar geologic history, it will be helpful to discuss the origin of the most common lunar landforms. Outside the maria, the craters are of course most important, because most lunar topographic features are craters, parts of craters, or clearly crater-related (e.g., rays). It has been recognized for many years, since the work of Gilbert (1893), that there is a continuum from ray craters like Tycho (Figure 8) to the circular mare basins such as that occupied by Mare Imbrium, apparent differences among craters being largely the result of age, erosion, and mare filling. Tsiolkovsky (Figure 9) is the best link between ray craters and the mare basins (Figure 10). Putting aside for the moment the many circular features that do not belong to this continuum, it is clear that proof of a particular origin for the ray craters would have major implications for the evolution of the moon's topography in general.

An impact origin for the ray craters is indicated by several lines of more-or-less independent evidence. First, meteorites and other extraterrestrial bodies

(such as the Tunguska object) are seen to hit the earth or its atmosphere frequently; a priori, similar objects must hit the moon's surface. It has been repeatedly shown (Baldwin, 1964, 1965; Gault, 1970) that the lunar surface must be heavily cratered by these relatively small objects, which should have produced a layer of rubble. Such a layer, the regolith, has now been investigated first-hand with the Apollo missions, and has been found to have the predicted petrographic and physical properties. A second line of evidence, related to the first, is the continuity of dimensions and form between terrestrial explosion and known impact craters and the lunar craters of all sizes. The best demonstration of this continuity is by Baldwin (1963), whose depth-diameter plots are well-known. The first high-resolution pictures of the mare surface, from Ranger VII, permitted Baldwin (1964) to strengthen this argument by filling the gap between terrestrial craters and telescopically-resolvable lunar craters. The small mare craters he tabulated are the size of those which have now been studied on the ground by Apollo astronauts, and whose impact origin is well-documented. Further pre-Apollo evidence for the impact origin of large lunar craters presented by Hartmann (1965) has now been strikingly verified by radio-metric mare dates. By comparing the formation rate of terrestrial and lunar craters, using the well-studied Canadian impact structures (Dence, 1965) for the terrestrial rate, Hartmann calculated the age of the maria to be 3.6 billion years — the most accurate published pre-Apollo estimate. Finally, the lunar ray craters have been shown to resemble known terrestrial impact craters in most morphological and structural aspects (Shoemaker, 1962) if allowance is made for size, age, and other factors. This evidence is of course somewhat subjective; Green (1965) in particular has found many morphologic similarities between lunar craters and calderas. The recent atlas of volcanic landforms (Green and Short, 1971) includes many examples of these similarities.

Despite this evidence for the impact origin of most lunar craters, there are a number of complications that should be briefly noted. First, many of these craters, and the mare basins, are filled with mare material, and have obviously undergone extensive volcanic activity at some time, although they have probably served simply to localize the eruption of independently-generated magmas. Second, the disparity in small crater density among flow units (Figure 8) surrounding Tycho — the most typical ray crater — suggests that these flows may be volcanic rocks erupted considerably after the supposed main impact (Gault, et al., 1968). There is, then, evidence for considerable volcanic or pseudo-volcanic activity in and around the ray craters even if the main process involved was impact.

Although the majority of lunar craters appear to belong to the Copernicus-Imbrium series just discussed, there are a large number of circular structures that probably do not. The chain craters, such as those of the Hyginus Rille (Figure 11), are generally considered to be of internal origin because of their

obvious structural control (Fielder, 1965, p. 123). More debatable is the origin of features like the Flamsteed ring (Figure 12); from its morphology, relation to mare ridges, and local superposition on mare craters, O'Keefe, et al., (1967) inferred this series of hills to be a ring of acidic extrusives rather than a flooded pre-mare (impact) crater. A number of craters intermediate in size between the Flamsteed ring and the chain craters are also considered volcanic (McCauley, 1968) because of their morphologic differences from Copernicus-type craters of the same size and relative age (Figures 13 and 14). In summary, there are probably many volcanic craters, some of them scores of kilometers in diameter, on the moon even if the majority are of impact origin.

Other lunar landforms that should be mentioned for completeness include the mare ridges (Figures 1 and 15), mare domes (Figure 15), and the rilles (Figures 15, 16, and 17). The first two are clearly post-mare volcanic features of some sort, and as such are relatively unimportant in understanding the geologic evolution of the moon as a whole. The rilles, in particular the sinuous ones, are probably formed by structurally-controlled volcanic activity (Lowman, 1969; Schumm, 1970), possibly gaseous eruptions. The evidence from Apollo 15, in particular the absence of inward dips along the Hadley Rille (Figure 17), tends to weaken the lava tunnel theory proposed by Greeley (1971).

EVOLUTION OF THE MOON

From the objective evidence of relative ages, absolute ages, and studies of returned samples, and assuming an impact origin for most lunar craters and mare basins, the geologic evolution of the moon has been reconstructed. It can be conveniently divided into four main stages, summarized in Table 2:

Stage I — Formation and rapid heating;

Stage II — First differentiation, formation of mare basins and Archimedean craters, and highland vulcanism;

Stage III — Second differentiation and mare lava eruptions;

Stage IV — Development of post-mare features (ray craters, volcanic craters and minor flows, rilles, small craters, landscape degradation).

Stage I (4.7-4.6 billion years ago)

All the modern theories of the moon's origin — independent origin, capture, and several variations of the fission theory — are currently viable to the extent that

each is still advocated by competent authorities. However, lunar exploration since 1969 has put new limitations on all theories of origin.

The first of these limitations is age. Studies of the moon's dynamical history by Macdonald (1964) and others have indicated that the earth-moon system might be considerably younger than the earth itself (4.6 billion years). Radiometric dating of returned lunar samples now shows this to be incorrect; the earth and moon evidently have the same age. The moon's age has been determined from that of the soil, which, as mentioned previously, is about 4.6 billion years. In principle, this might be the date at which the moon formed elsewhere, to be later captured by the earth. However, there is no good geologic evidence on the earth or moon of such an event later than 4.6 billion years ago. An important aspect of the moon's age, which has been determined by several methods (Tatsumoto and Rosholt, 1970; Albee, et al., 1970), is that it is very close to the age of the solar system, judging from the radiometric ages of meteorites tabulated by Wood (1968).

Several lines of evidence suggest that the moon formed in a time surprisingly short by geologic standards. A possible maximum figure is Hohenberg's (1970) estimate of 176-179 million years for the interval between the last nucleosynthetic event and the beginning of ^{129}Xe retention in meteorites. A specific and much shorter formation period for the moon was derived by Papanastassiou, et al. (1970a) from the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of Mare Tranquillitatis basalts. This ratio is very low, differing only slightly from the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of achondritic meteorites; i. e., the moon has very primitive strontium. Papanastassiou and his colleagues interpret this as meaning that the moon and the stoney meteorites separated from the solar nebula in less than about 10 million years, 4.6 billion years ago. Even shorter formation periods have been suggested by A. G. W. Cameron (1970) — 1000 years — and by Öpik (1967) — 350 years.

Such a rapid process may strike the geologist as unlikely, compared to the times involved in evolution of the earth's crust. But it seems likely, from its age, that the moon's formation was primarily astrophysical rather than geological in nature. Astrophysical processes, involving turbulent gases, plasmas, and dust, rather than large solid bodies, are generally fast by geological standards. Variable stars frequently have periods of hours, and there is some evidence for stellar evolution in individual stars over a period of decades. It is possible that even the late stages of star formation have been observed; Herbig, in 1954, found two star-like objects on photographs of the Orion Nebula that had not been there only eight years before (R. C. Cameron, 1968). From a cosmological viewpoint, then, there seems no inherent reason why the moon could not have formed rapidly.

Table 2

Tabular Summary: Geologic Evolution of the Moon

Stage ¹	Events ²	Evidence
I (4.7-4.6)	<p>(a) Formation of moon, near the earth or from it, by precipitation or fission (?). Preceded or accompanied by depletion of proto-moon material in volatile elements (e.g., K, Pb, Rb). Process of formation took about 10 million years, possibly less than 1000 years.</p> <p>(b) Strong heating, to temperatures over 1000°C, of outer parts of moon in later stages of formation, from energy of accretion, fission, and tidal interaction with earth. Short-lived isotopes (e.g., aluminum 26) possibly important.</p>	<p>(1) Age of oldest lunar soil component, 4.6 b.y., sets lower limit to time of moon's formation.</p> <p>(2) Similar ⁸⁷Sr/⁸⁶Sr ratios in Apollo 11 and 12 samples and achondritic meteorites indicates separation of moon from solar nebula in less than 10 m.y., 4.6 b.y. ago.</p> <p>(3) Radiogenic gas (Ar, He, Xe) retention in meteorites began 4.6 b.y. ago.</p> <p>(4) 176-179 m.y. interval between last stages of nucleosynthesis and radiogenic xenon retention (from iodine 129) suggests rapid formation of planetesimals.</p> <p>(5) U-Pb concordia diagrams for Apollo 11 samples indicate last major U-Pb fractionation in moon 4.65 b.y. ago.</p> <p>(6) Apollo 11, 12, and 14 samples systematically low in volatile elements compared to similar terrestrial rocks.</p> <p>(1) Evidence for early differentiation and magma generation discussed below implies early heating.</p> <p>(2) Present electrical conductivity and temperature profiles implied by magnetometer data suggest melting to depths of not more than 500 km.</p> <p>(3) Calculations on energy of fission and accretion indicate high temperatures attained.</p> <p>(4) Remnant magnetism of mare rocks suggests early lunar magnetic field, possibly produced by internal dynamo mechanism.</p>
II (4.6-3.7)	<p>(a) First differentiation of moon, by partial melting, secondary magmatic differentiation, and vulcanism, to form global crust (now lunar highlands) of aluminum-rich basalt, gabbroic anorthosite, anorthosite, and minor acidic rocks.</p>	<p>(1) Relative age of highlands inferred from great density of craters and superposition of maria.</p> <p>(2) Absolute age of highlands (ca. 4 to 4.5 b.y.) inferred from Rb-Sr whole rock ages of 12013, LR-1, anorthosite 15415, and other allochthonous mare samples (e.g., KREEP).</p> <p>(3) Composition of highlands inferred from Apollo 14 Fra Mauro samples, allochthonous Apollo 11 and 12 mare samples, Al/Si ratios from Apollo 15 X-ray fluorescence experiment, and Surveyor VII alpha-scattering experiment.</p> <p>(4) Existence of highland volcanic flows indicated by layering in Mt. Hadley and Hadley Delta, by level intercrater areas in highlands, and by old highland mare areas (e.g., Schiller basin).</p>

1. Time () in billions of years before present.

2. Sub-events () in chronological order, unless noted otherwise.

Table 2 (continued)

Stage ¹	Events ²	Evidence
II (4.6-3.7)	<p>(b) Formation of pre-mare impact craters by infall of nearby bodies related to origin of moon, during recession of moon from earth.</p> <p>(c) Shear faulting on NW and NE directions, caused by N-S compression of moon during recession from earth and slowing of rotation.</p> <p>(d) Infall of proto-moons or large fission fragments to form circular mare basins, in order: Nectaris Smythii Serenitatis Humorum Crisium Imbium Orientale (Other smaller basins also formed by impact; exclusion arbitrary.)</p> <p>(e) Formation of Archimedian generation craters (after mare basins, but before mare filling).</p> <p>(f) Eruption of highland volcanics such as Cayley formation. NOTE: roughly contemporaneous with formation of Archimedian craters.</p>	<p>(1) Post-highland crust early intense bombardment inferred from high crater density, coupled with survival of highland layering and intercrater smooth areas.</p> <p>(2) Impact origin of highland craters indicated by morphologic similarity to post-mare Copernican and Eratosthenian craters.</p> <p>(1) Telescopic study and Lunar Orbiter photographs show existence of "lunar grid" consisting of NW and NE trending shear (?) faults with slight horizontal displacement.</p> <p>(2) Surveyor and Apollo surface photos show local NW and NE lineaments concordant with regional pattern.</p> <p>(1) Morphologic continuity between Copernican craters (q.v.) and circular mare basins implies impact origin for latter.</p> <p>(2) Impact origin of Imbrium basin suggested by fragmental nature of Apollo 14 Fra Mauro formation samples.</p> <p>(3) Relatively low crater density of Fra Mauro formation and similar units indicates post-highland crust age.</p> <p>(4) Ejecta from youngest mare basin (Orientale), Helvelius formation, not deposited on O. Procellarum surface, indicating pre-mare age of circular mare basins.</p> <p>(1) Archimedes and similar craters are in or on rims of mare basins, so must be post-basin.</p> <p>(2) Mare lavas fill and partly surround Archimedes, so crater is older than mare lavas.</p> <p>(1) Cayley formation is not overlain by Fra Mauro formation, but is more heavily cratered and lighter-toned than Imbrium mare material, showing post-basin, pre-mare age.</p> <p>(2) Crater density in Ptolemaeus (Cayley formation) intermediate between that of terrae and maria.</p>

1. Time () in billions of years before present.

2. Sub-events () in chronological order, unless noted otherwise.

Table 2 (continued)

Stage ¹	Events ²	Evidence
III (3.7-3.2)	Second differentiation of moon, by repeated localized partial melting of outer 500 km of moon to produce iron-rich basaltic magma, erupted in multiple flows to form maria. Main eruptions occurred in interval of a few hundred million years, with minor mare eruptions considerably later. Tsiolkovsky mare lavas probably much younger, possibly Eratosthenian.	<ol style="list-style-type: none"> (1) Igneous nature and internal derivation of mare material shown by Apollo 11, 12, and 15 samples. (2) K-Ar and Rb-Sr data give concordant ages of crystallization and magma generation (3.2 to 3.7 b.y.) for basalts from M. Tranquillitatis, O. Procellarum, and P. Putredinus. (3) Variance in initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios among mare basalts suggests several different sites of magma generation rather than one for each location. (4) Layering in maria (e.g., Hadley Rille) shows multiple flows; also inferred from crater morphology and sample analysis.
IV (3.2 to present)	<p>Concurrent events:</p> <ol style="list-style-type: none"> (a) Local mare and highland volcanism, forming Marius Hills, Flamsteed ring, chain craters, sinuous rilles, Gambart-type craters, Sulpicius Gallus formation, and other features. Minor gas eruptions from deep sources. (b) Minor tension faulting, in and around maria and in highlands. (c) Sporadic impact of meteoroids from asteroid belt and of cometary fragments, forming ray craters (including Eratosthenian) such as Copernicus; possibly followed by short-lived volcanic activity. 	<ol style="list-style-type: none"> (1) Evidence for volcanic origin from photogeology and similarity to terrestrial volcanic landforms. (2) ALSEP instruments indicate low level of deep seismic activity and possible gas eruptions. (3) Evidence for relative age given on USGS maps cited in text. <p>Photogeology: Straight Wall, "normal" rilles, Apennine front.</p> <ol style="list-style-type: none"> (1) Impact origin indicated by morphology, terrestrial analogues, and age of maria predicted from crater density and meteoroid flux. (2) Relative age indicated by superposition and albedo. (3) Post-impact volcanism indicated by variance in crater counts among flow units.

1. Time () in billions of years before present.

2. Sub-events () in chronological order, unless noted otherwise.

Table 2 (continued)

Stage ¹	Events ²	Evidence
IV (3.2 to present)	Concurrent events: (continued) (d) Continual slow landscape degradation and regolith formation by meteoritic and secondary fragment impact and ejecta deposition, thermal shock, and radiation. Seismic waves from impacts possibly effective.	(1) Impact origin of regolith indicated by petrography of soil and breccia samples. (2) Mass wasting effects visible at all Surveyor and Apollo landing sites. (3) Cosmogenic isotopes indicate exposure times and hence erosion and turnover rates.
Present condition of moon: Cold and rigid to depths of about 500 km, but with P, T conditions for magma generation at greater depths. Occasional minor vulcanism, largely gaseous, and accompanying seismic activity, indicated by lunar transient phenomena and ALSEP instruments. Periodic mild moonquakes triggered by earth's attraction at perigee of moon's orbit.		

1. Time () in billions of years before present.

2. Sub-events () in chronological order, unless noted otherwise.

Still another condition of the moon's origin which can now be more closely specified is that of temperature. Since about 1950, planet formation has generally been considered a low-temperature process (Urey, 1952), as has the origin of the moon. However, it now appears that the moon or a large portion of it became very hot during or shortly after its formation, regardless of just what the formative process was. The arguments for a hot moon have been summarized by Baldwin (1970) and Lowman (1970); they appear to be the following.

The strongest direct evidence for a high-temperature origin is the age of the mare lava flows, which points firmly to major basaltic magma generation as early as 3.7 billion years ago. This in turn implies temperatures at this time of at least 1200°C in a substantial part of the moon's volume. The high-temperature stage can be pushed back even farther by consideration of the highland ages. For reasons to be discussed under Stage II, the highland rocks are thought to have formed by partial melting of the moon's interior; the radiometric data indicate that this happened 4.6 billion years ago. Evidence that the origin of the moon itself was a high-temperature process is found in the chemical composition of both mare and highland rocks, which are consistently low in the volatile elements compared to terrestrial rocks of similar mineralogy (Taylor, et al., 1971). The low Rb/Sr and K/U ratios have been interpreted by Gast and Hubbard (1970), Ringwood (1970), and others as the result of high temperature fractionation

during the moon's formation, although Anders and his colleagues (1971) consider this volatile loss to have occurred earlier, in the solar nebula, rather than on the moon.

Indirect evidence for a high-temperature origin for the moon comes from its time and duration of origin. As mentioned earlier, the moon probably formed within 200 million years of the end of nucleosynthesis, although no evidence for extinct radioactivity in lunar rocks has yet been reported. Thus short-lived isotopes such as ^{244}Pu could have made an appreciable contribution to the moon's temperature of formation. Also, a very short period of formation favors high temperatures, since the energy added by accretion might not be lost (by radiation). (See Hanks and Anderson (1969) for discussion of this problem as it applies to the earth and Mars.)

A final piece of evidence for an initially hot moon comes from the surprisingly strong local magnetic fields measured on the lunar surface: 38 gammas for the Apollo 12 site and 103 gammas (steady values) at the Apollo 14 site (Dyal, et al., 1971). For comparison, the quiet sun interplanetary field at one A.U. has a strength of about 5 gammas. The lunar values are evidently remnant magnetism resulting from a fairly strong ambient field at the time the local rocks were formed; if this ambient field was of lunar origin, it might imply an internal dynamo mechanism and a hot core. However, Dyal and his colleagues point out that other explanations, not requiring a hot moon, are also possible.

Against this array of indications for a high temperature origin must be placed the studies of Ness (1968) and of Sonett, et al., (1971) with the Apollo 12 ALSEP magnetometer, whose results have just been cited in support of a hot moon. From the electrical conductivity of the lunar interior, calculated in turn from the magnetometer data, Sonett, et al., estimated the present temperature of the moon to be less than 1000°C , and concluded that the moon has not been differentiated to depths greater than about 500 km. Sonett specifically interpreted these results, at the Apollo 12 Lunar Science Conference, as support for a cold origin of the moon. They at least put further restraints on the thermal history if the present thermal gradient has been calculated correctly. Perhaps the most plausible compromise at this time is that melting in the moon was partial, and restricted to the outer 500 kilometers.

The problem of the moon's origin can not be settled by geological evidence alone; dynamical restrictions in particular are important (Kaula, 1971) in deciding among capture, fission, and independent origin. However, the geological evidence considered so far indicates at least some boundary conditions: the moon was formed about 4.7 billion years ago, in a period of not more than about 10 million years and possibly less, and the process of formation heated much of the moon to temperatures over 1000°C .

Stage II (4.6 to 3.7 billion years ago)

The next stage in the moon's evolution, the first billion years or so after its origin, is of particular geological interest because there is no direct evidence of the corresponding stage on earth; the first rocks ever collected on the moon were older than any known terrestrial rocks. This pre-mare stage has six main events (Table 2).

The first and most important event, II (a), after the moon's formation was development of a global crust which still comprises most of the lunar surface: the highlands, or terrae. The time at which most of this crust formed can be placed only approximately between 4 and 4.6 billion years ago, on the basis of radiometric dates of soil, breccia, and individual exotic mare rock fragments thought to have come, by impact, from the highlands (Papanastassiou, et al., 1970; Papanastassiou and Wasserburg, 1970). The only true highland date so far is a preliminary determination of 4.15 billion years for the anorthosite sample from the Apennine front (which may be float).

The nature of the highlands is still largely unknown, and they doubtless have a wide variety of rock types. However, several lines of evidence bearing on highland composition are beginning to converge. The best pre-Apollo information is from the Surveyor VII alpha-scattering experiment (Patterson, et al., 1970), which provided analyses of undisturbed surface, a rock, and a trenched area at the landing site 30 kilometers north of Tycho (Figure 8), on a flow unit. The average soil composition (Table 3) resembles anorthositic gabbro, and Patterson, et al., calculated a possible mineral composition of 62% (weight) feldspar and 38% pyroxene.

The alpha-scattering experiment also indicated the uranium content at the Surveyor VII to be lower than at the Surveyor V site in Mare Tranquillitatis, a result that would not be expected if the terrae and maria correspond to the earth's continents and oceans respectively. The terrae appeared instead to be enriched in aluminum and calcium, relative to the maria. The television pictures from Surveyor VII provide possible confirmation of this feldspathic composition, showing large light-toned crystals in the local rocks that could be plagioclase phenocrysts (Figure 18); Jackson and Wilshire (1968) show a similar example from another Surveyor VII photograph.

Further indications of the highland composition are provided by exotic fragments collected from the maria at the Apollo 11 and 12 sites. The best-known of these are the "anorthosites" described in detail by Wood, et al. (1970) from Apollo 11: plagioclase-rich fragments, grading into gabbroic anorthosites, with extremely calcic compositions (An_{96-98}). This high anorthite content distinguishes them from terrestrial massif anorthosites, which generally have plagioclase

Table 3

Surveyor VII Soil Analysis and Terrestrial Rocks

	Surveyor VII Soil ¹	High-alumina Basalt ²	Stillwater Gabbro ²
SiO ₂	46.1	49.8	50.5
Al ₂ O ₃	22.3	19.9	20.2
CaO	18.3	11.1	14.1
MgO	7.0	4.2	8.0
FeO	5.5	9.8	5.2
Na ₂ O	0.7	3.4	1.7

1. Oxide composition calculated by Patterson, et al., (1970); CaO and FeO based on elements in mass number ranges 30 to 47 and 47 to 65, respectively.
2. From compilation by Jackson and Wilshire (1968). Basalt listed had feldspar phenocrysts. Jackson and Wilshire considered Surveyor VII analysis to resemble high-alumina basalt.

with An₄₅ to An₆₅, according to Anderson (1968). Gabbroic anorthosites occur with the lunar anorthosites, and are much more abundant (Wood, et al., 1970). Another widespread exotic rock type consists of gray fragments found at both the Apollo 11 and 12 sites (Smith, et al., 1971); these have been called "norite" by Wood, et al., (1971) and "plagioclase hypersthene basalt" or "non-mare basalts" by Hubbard and Gast (1971). This material has an unusually high concentration of lithophile trace and minor elements, especially potassium, rare earth elements, and phosphorous, hence the acronym KREEP. In addition to its occurrence as isolated fragments, KREEP has also been found in the 4.0 billion year old microbreccia 12013 (metamorphic age; Asylum, 1970). This sample, probably the most intensively studied single rock in the history of geology, is notable for its high SiO₂ content of 61%, which is partly due to fragmental potassium feldspar-quartz felsite (James, 1970). The fragmental nature of the felsite suggests that it may have originally been derived from a discrete occurrence of such rock, before being consolidated into the 12013 breccia. This and other Apollo 12 soil samples are of particular interest because the landing site was on a Copernicus ray, and hence the exotic fragments could represent terra material underlying the mare in which the crater Copernicus was excavated.

The Apollo 14 landing site was on nominal highland material — the Fra Mauro formation. This pre-mare formation is generally interpreted as ejecta from the Imbrium basin, and may not be representative of the highland crust in general (Adler, et al., 1971). The Apollo 14 samples were almost all fragmental rocks that proved on closer study to be polymict breccias, frequently with three generations of breccia in one specimen. The breccia fragments consisted chiefly of basalt, "anorthosite," fragments of pyroxene, olivine, plagioclase, and other minerals, and glass. Although the components of the Fra Mauro breccias were generally similar to the rocks and minerals from the Apollo 11 and 12 mare sites, the Apollo 14 samples (LSPET Report, 1971) were notably richer in plagioclase and in lithophile elements, in particular K, Rb, U, Th, Ba, and Zr. Chemically, they generally differ from the Apollo 12 rocks in having higher SiO_2 and Al_2O_3 but lower FeO contents.

Only a few crystalline rocks were collected by the Apollo 14 astronauts, and all described so far (LSPET Report, 1971) are basalts. They are significantly richer in plagioclase than are the mare basalts. This characteristic is of particular interest since the report of Husain, et al., (1971) giving argon 40 - argon 39 ages of 3.77 billion years for these rocks, and thus demonstrating that they probably represent the pre-mare crust.

Only preliminary reports from the Apollo 15 mission are yet available. Most of the rocks collected by the crew were described as either basalt or breccia; the large specimen of monomineralic anorthosite has already been mentioned. An outcrop sample, 15555, examined at Goddard Space Flight Center, had been collected from the edge of the Hadley Rille, and thus gives some idea of the nature of the local mare rocks. It is an iron-rich basalt, similar in all major aspects to the other mare samples from previous missions.

As mentioned previously, the Apollo 15 mission carried experiments for remote compositional sensing of the moon's surface from orbit. The X-ray fluorescence experiment (S-161) measured the intensity of X-rays excited from the lunar surface by solar X-rays, as a means of determining the relative abundance, along the flight path, of major rock-forming elements such as aluminum, silicon, and magnesium (Adler, et al., 1971). At this time, only the Al/Si intensity and concentration ratios have been calculated, with low spatial resolution (on the order of 110 km). However, they show clearly (Figure 7) that the highlands are enriched in aluminum relative to the maria. The Al/Si ratios of the highlands near the eastern limb do not seem high enough for pure anorthosite; the anorthositic gabbro fragments from Apollo 11 and 12 seem closer to the highland compositions indicated by the S-161 experiment, although there could well be local occurrences of anorthosite. This point, if verified by further data reduction, has important petrologic implications, in that anorthositic gabbros (equivalent to feldspar-rich basalts) are easier to account for, especially as extrusives, in

large quantities than are the monomineralic anorthosites. The Al/Si ratio of KREEP, calculated from the analyses of McKay, et al., (1971) and Meyer, et al., (1971), is only about half that of the eastern highlands; thus this material, like the anorthosites, does not seem to make up large highland areas although it probably occurs locally.

Little information is available at this time from the Apollo 15 gamma-ray spectroscopy experiment. However, it appears from preliminary data (J. Trombka, personal communication) that the maria are higher in the radioactive elements (U, Th, ^{40}K) than the highlands. This somewhat surprising result is in agreement with the Luna 10 gamma-ray spectrometer, which indicated the gamma-ray intensity over the maria to be 1.15 to 1.2 times that over the highlands (Vinogradov, et al., 1966). The low gamma-ray intensity found by the Apollo 15 experiment appears to rule out large areas of granite or equivalent lithologies in the highlands.

In summary, we see that, despite the preliminary nature of the surface and orbital compositional information, the general outlines of highland composition are emerging. It is clear that the highlands are chemically different from the maria, although there may be all gradations between the two; it should be remembered that mare material, or something with similar topography, occurs at many places in the highlands. Extreme compositions formerly proposed for the highlands, such as chondritic meteorites and granite, can be ruled out, at least in large amounts. The most likely rock type making up the bulk of the highland crust appears to be feldspathic basalt, considerably lower in iron and higher in aluminum than the mare basalts, occurring as multiple flows and possibly intrusives. There are probably local occurrences of anorthosite, KREEP, and 12013-type felsite, presumably thoroughly mixed and distributed by repeated cratering events. The processes by which the highland crust formed can not be inferred from presently available chemical and petrologic data alone, and a discussion of highland evolution will therefore be deferred until the other events of Stage II have been outlined.

As shown in Table 2, the next event that can be identified in the pre-mare stage is the formation of the many old highland craters (presumably by impact, as previously discussed). These old craters are generally thought to represent the last stages of the moon's accretion (Gilbert, 1893; Baldwin, 1963), and were so explained in the first version of this paper (Lowman, 1970), in which it was concluded that the highland crust formed while cratering was still intense. However, some of the many striking surface photographs by the Apollo 15 crew throw strong doubt on this possibility. As shown in Figures 19, 20, and 21, the pre-Fra Mauro crust exposed in the Apennines, specifically Mt. Hadley and Hadley Delta, displays at least two sets of orderly layering. Although the nature and

origin of these layers are not understood, it seems likely, from its dip, that at least one set — the eastward-dipping layers of Silver Spur and Hadley Delta — is primary; that is, it existed before the Imbrium basin was formed. However, if the pre-mare basin highland crust was formed while intense cratering was in progress, such layering could hardly have developed or survived; we should expect the subsurface terrae structure to be chaotic rubble. Short and Forman (1971) have calculated the depth of ejecta from the visible highland craters alone to be 1.5 to 2 kilometers.

Hartmann (1966), in a study of early lunar cratering, pointed out that a chaotic highland structure would be expected if the highland craters represent the last stages of the moon's accretion, while observing that in fact the oldest highland surfaces did not seem to consist of "crater on crater" (Figure 22). He tabulated six theories that might account for the early intense bombardment, and predicted lunar and planetary criteria that could be used to evaluate each. Since Hartmann presented grounds for rejecting most of these theories, it is not necessary to review each of them. The most likely theory, in Hartmann's view, is that the early craters were formed by small bodies swept up by the moon as it receded from the earth. The evidence shown here in the Apennine front indicates that the highland cratering occurred after most of the highland crust had formed; it does not represent the last stages of accretion, and thus supports Hartmann's opinion.

The next event in the pre-mare stage is difficult to place chronologically: the development of two sets of faults (the "lunar grid") on NE and NW trends. This event is placed in Stage II because such faults are found in the pre-mare southern highlands (Fielder, 1965; Strom, 1964). However, photographs from Surveyor spacecraft and from Apollo landings reveal post-mare small lineaments at the landing sites (Shoemaker, et al., 1970). These tend to follow the recognized grid trends (Schaber and Swann, 1971), and may be old fractures re-activated by later seismic or impact events. The evidence bearing on the nature of the lunar grid faults is not strong, although Fielder (1965, p. 106 ff) shows possible examples of horizontal offset. Wrench faulting on NE and NW directions would be consistent with north-south compression resulting from a change in the moon's rotation rate or distance from the earth.

The next event in Stage II, occurring after most of the highland crust and craters had formed, was the excavation of the circular mare basins, presumably by the impact of large bodies. Although only six basins are listed in Table 2, many large craters might be considered small maria; Stuart-Alexander and Howard (1970) found 23 additional circular basins over 300km wide. The relative age of the mare basins listed as a group is demonstrated by the fact that they are filled by mare lavas, but their ejecta (such as the Fra Mauro formation) overlies more heavily-cratered highland terrain. The ages of the large basins

relative to each other has been inferred from the degree of post-basin cratering around each or, where recognizable ejecta blankets overlap, superposition (Mutch, 1970, Figure VI-14). An important point here is that the ejecta from the Orientale basin does not seem to be superimposed on the surface of Oceanus Procellarum; since the Orientale basin is obviously the youngest, this means that all the listed basins pre-date the last major mare eruptions.

It should be pointed out that formation of the mare basins represents something of a discontinuity in the moon's early evolution. The moon was undergoing the early intense bombardment previously discussed, by many small objects, when it was hit by several very large ones in a relatively short period. Baldwin (1963) estimates the Imbrium planetesimal to have had a diameter of between 64 and 190 kilometers, depending on what the impact velocity was. At least two sources for these large bodies can be suggested. They might have been fragments detached in the fission process thought by some to have formed the moon (O'Keefe, 1969), captured as the moon receded. Alternatively, they might have been small proto-moons that had formed at the same time as the present moon, and their infall a process of sweeping up by it (MacDonald, 1964).

Craters such as Plato and Archimedes (Figure 10), and Sinus Iridum, represent the next group of features developed in the pre-mare stage. These craters have extremely important implications for the origin of the mare magmas and for crustal evolution in general, and hence will be discussed in some detail. The Archimedes-type craters are in or on the borders of circular mare basins and are at least partly filled or covered with mare lavas. They are surprisingly common, occurring in all the circular maria. The relative age is unambiguous: they must be younger than the mare basins, or else they would have been destroyed when the basins were formed. But they must be older than the mare lavas which fill them. Thus these craters demonstrate that a significant time elapsed between formation of the mare basins and eruption of the lavas. Independent demonstration of this interval is also provided by the difference in crater counts between the mare and terra parts of the Orientale basin (Gault, 1970). The basin-mare interval has been commonly overlooked (e.g., Levinson and Taylor, 1971), although Baldwin (1963, 1970), Shoemaker (1964), and Hartman (1966) have repeatedly called attention to it. We shall return to the subject in discussing the origin of the mare magmas.

Still another group of terrain features evolved before eruption of the maria: the heavily cratered, high-albedo terrain inside highland craters such as Ptolemaeus (Figure 23). This terrain has been named the Cayley formation by Howard and Masursky (1968), and interpreted by them as possible volcanic material. Regardless of its actual origin, the Cayley formation, like the Archimedean craters, is younger than the mare basins but older than the maria. Its post-basin

age is shown by the fact that the Fra Mauro formation does not overlie it, even relatively close to Mare Imbrium. But it is locally embayed by mare material (Mutch, 1970, p. 137), and has a higher albedo and primary crater density (Baldwin, 1964, Figure 5) than the maria. Thus the Cayley formation was formed in the basin-mare interval, and although it was probably contemporaneous with the formation of Archimedean craters, its age again emphasizes the fact that the lavas did not immediately follow basin formation.

Stage III (3.7 to 3.2 billion years ago)

We come now to the evolution of the best-known lunar terrain features: the maria. Mare terrain has been investigated by nine soft-landing spacecraft, Russian and American, and by three Apollo missions, and the lunar literature is consequently dominated by studies of mare topography, structure, and composition. Accordingly, I shall summarize only the major aspects of the subject: When were the maria formed? What are they like? How did they originate?

The relative ages of the maria are clear, from superposition and crater counts. Absolute ages have been determined for samples from three sites, as previously mentioned, and range from 3.2 to 3.7 billion years. Despite some early uncertainties in the radiometric results, there is now reasonably good agreement among the Pb-U, Rb-Sr, and K-Ar dates. The agreement between Rb-Sr ages, representing Rb-Sr fractionation, and K-Ar, representing crystallization, suggests that the mare magmas were generated shortly before they were erupted.

The structure and composition of the maria have been investigated in some detail, both locally (by landing missions) and regionally (by photogeology and remote sensing). Typical chemical compositions have been given in Table 1. Petrographically, the crystalline rocks can be considered basalts, despite a number of distinct differences between them and terrestrial basalts (Mason, 1971; Melson and Mason, 1971). The chief mineralogical peculiarities of the lunar mare basalts are high content of mafic minerals, the high anorthite content of the plagioclase (generally over An₇₅), and the nearly complete absence of hydrothermal alteration products. The corresponding chemical characteristics, compared to terrestrial basalts, are the high FeO, MgO, and TiO₂ contents, and the low alkali contents. There is enough variation in modal composition among the various mare basalt samples from any one site to indicate derivation from a number of eruptive or intrusive units.

Topographically, the maria are notable for their flatness, scarcity of flow fronts, and great areal extent, characteristics that would be expected of a basic or ultrabasic lava. Photogeologic studies, in particular those by Quaide and Oberbeck (1968), suggested before the Apollo missions that the maria were composed of many layers. This has now been confirmed, indirectly by the variation

in mare samples and directly by the basalt layers exposed in the Hadley Rille (Figure 24).

Several conclusions can be drawn about the origin and evolution of the maria. First, it is perfectly clear that the liquids which solidified to form the maria were not melts produced by the presumed basin-forming impacts, contrary to earlier views (Urey, 1952). The mineralogy and textures of mare crystalline rocks, though peculiar in some ways, are typically magmatic, and easily distinguished from impact melts such as those described by Dence (1971) by their homogeneity, phenocrysts, and freedom from shocked inclusions. In addition, the maria were erupted well after the basins were formed, whereas impact melts form essentially instantaneously. Finally, the moon should have the same bulk composition as the maria if the latter were simply impact melts, but Ringwood and Essene (1970) have shown that this is impossible because the basalt-eclogite transition would raise the moon's density above the actual value.

A second conclusion is that the mare magmas were generated by partial melting of the outer 500 kilometers or so of the moon. This is indicated, first, by the evidence previously cited that the mare basins were formed "dry" (Baldwin, 1970), except for possible impact melts as yet unrecognized. This fact is petrologically as well as structurally important, for many theories of genesis for the mare magmas (e.g., Wood, et al., 1970; Biggar, et al., 1971) involve impact penetration or foundering of a solid (anorthositic?) crust overlying a liquid basaltic magma reservoir. Further evidence for magma generation by partial melting is given by Ringwood (1970) and Brown (1970), drawn from detailed chemical and mineralogical studies that can not be reviewed here. Finally, it should be pointed out that basaltic magmas in the earth are essentially proven, by seismic and petrologic evidence, to form by partial melting; to demonstrate a completely different origin for the fundamentally similar lunar basalts would require extremely strong evidence, which so far has not been produced.

The location of this partial melting is not clear. The thermal gradients indicated by the Apollo magnetometer results imply depths not greater than about 500km, but Smith, et al., (1971) point out a number of problems associated with relatively shallow melting. An interesting and as yet not understood aspect of the process is that variance in initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios among Apollo 12 samples suggests that there were many individual sites of magma generation, each with a characteristic ratio (J. Philpotts, personal communication).

A further conclusion about the mare magmas is that, although they were primary in the sense of forming from previously solid material, they did undergo considerable differentiation. The evidence for this comes primarily from the Apollo 12 rocks, which are more representative of the maria than those from

Apollo 11. The differentiation appears to resemble in general aspects that of the Skaergaard intrusion (Wager and Brown, 1967), showing considerable crystal/liquid fractionation and late-stage iron enrichment, with the final liquid having a granophyric composition. It is not yet known if substantial amounts of the granitic residual liquid were ever segregated. However, the Marius Hills volcanoes (McCauley, 1967) and the Flamsteed ring can be interpreted as resulting from extrusion of late-stage siliceous differentiates. The mare ridges might also represent the final intrusion or locally extrusion of the last mare differentiates.

Each mare was formed by many eruptions of lava — possibly hundreds or thousands (Baldwin, 1970). These eruptions were obviously localized in some circular mare basins, but occur at many other places, such as Mare Frigoris, Oceanus Procellarum, and Mare Australe (Lowman, 1969b) where the structural control is not obvious. From a broad viewpoint, the concentration of maria on the earthward side of the moon is of course a major problem. Stewart-Alexander and Howard (1970) point out that since the distribution of circular basins is probably random, the question is why the mare lavas were preferentially erupted on the near side. Smith, et al., (1971) consider the mare distribution related to the earth's gravitational attraction in some way. The problem is primarily geophysical, rather than petrological, and its solution must await further orbital studies of the moon's structure.

Stage IV (3.2 billion years ago to the present)

By the end of Stage III, around 3 billion years ago, much of the moon's present physiography had been developed, and its geochemical evolution was essentially finished. However, several conspicuous types of post-mare topography have since been formed. They were developed more or less concurrently, so the following summary is not chronological; relative ages of individual features are shown on the U.S.G.S. 1:1,000,000 lunar geologic maps.

The most conspicuous post-mare features are the ray craters and those such as Eratosthenes which, though now without visible rays, are also post-mare. The evidence for impact origin has been summarized previously, and in the following discussion such an origin will be assumed, without excluding post-impact volcanic activity.

The large ray craters and the Eratosthenian craters are much less abundant than are the highland craters of comparable size. If one assumes a linear rate of crater formation based on the present observed meteoroid flux, the calculated age of the southern highlands is impossibly high; Gault (1970) cites figures of 10 to 100 billion years. If most of these craters are of impact origin, the obvious implication is that the cratering rate in the moon's early history was far higher

than it is now, as we have seen. This can be explained in several ways, most of which imply that the bodies which produced the early (highland) craters were from a different source than those producing the later (ray) craters. Most authorities consider the post-mare craters to have been formed by bodies from the asteroid belt or by comet nuclei (e.g., Hartmann, 1970).

Various estimates of ray crater ages have been made on the basis of assumed meteoroid fluxes. However, the recent availability of absolute radiometric dates for the maria provides a new means of estimating post-mare crater ages. Wood and Hartmann (1970) have used the crater density of the Apollo 12 site, combined with a radiometric age of 3.4 billion years, to calculate the age of Tycho from comparative crater densities. They find Tycho to have an equal-size crater density of about 0.08 times that of the Apollo 12 site, corresponding to an age of 2.7×10^8 years. Similar ages for Tycho have been derived by Strom and Fielder, according to Hartmann. In terrestrial terms, then, Tycho is late Paleozoic, despite its fresh appearance.

The generally-accepted impact origin of the regolith and most small craters supports an impact origin for large craters such as Tycho. Hartmann (1967) has shown that diameter-frequency plots for the highlands and maria are smooth curves, parallel to each other in the 100 meter - 1000 km range. This implies, first, that most of the highland and mare craters were formed in the same way, and, second, that the small ones and large ones were formed in the same way; Hartmann considers impact the most likely process. The high-resolution surface photographs from Surveyor spacecraft have been used by Shoemaker, et al., (1967) to extend these curves down to the 0.1 meter size range (Figure 25), implying that the very small craters are also of the same origin. Study of the regolith reveals abundant shock features, indicating that these small craters formed by impact. The essentially complete continuity in geometry and size-frequency distribution between these and craters as large as the Imbrium basin suggests an impact origin for the latter.

Innumerable small impacts have, in the 3 billion years since the mare lavas were erupted, degraded the original lunar landscape everywhere in varying degrees. These small impacts, and those of secondary ejecta, are probably the main erosive agent on the moon, though an extremely slow one (Figure 26). Radiation and thermal shock are probably also effective, as evidenced by occasional rocks cracked in situ and by fillets of soil commonly surrounding rocks.

In addition to the pervasive impact cratering, there has clearly been considerable post-mare volcanic activity on the moon. The chain craters are one manifestation of such activity, although careful study is necessary to distinguish between internally-caused crater chains and those produced by strings of ejecta

fragments from large craters (Figure 3). The Marius Hills are also the result of post-mare igneous activity of some sort. The problem of whether the moon is still volcanically active is still debated. Of considerable interest are the dark terrain-mantling deposits mapped by Carr (1966) as the Sulpicius Gallus formation, and interpreted as Erathosthenian or Copernican volcanics.

To this morphologic evidence for post-mare vulcanism must be added that from several sources for present internal activity of some sort. First among these are the many reports of lunar transient phenomena observed telescopically. The 1958 Alphonsus emission spectrograms obtained by Kozyrev, suggesting C_2 bands, were followed shortly by the visual observations in 1963 by Greenacre and Barr of short-lived bright red spots around Aristarchus. Stimulated by these well-documented observations, Burley and Middlehurst (1968) and Cameron (1971) re-examined the astronomical literature and found similar observations as far back as the 18th century. These events (excluding obviously spurious ones) have generally been interpreted as gas eruptions, since no recently-formed deposits of material have been found at their sites on Lunar Orbiter photographs. Strong support for active degassing comes from Apollo 12 ALSEP and orbital science experiments. The cold-cathode-gage experiment in the Apollo 12 and 14 ALSEPs, which measures total gas pressure, has detected several gas events in which pressure increased by several orders of magnitude (Johnson, et al., 1971). Preliminary reports on the Apollo 15 orbital science experiments include early data from the mass spectrometer indicating natural degassing events distinct from spacecraft venting.

Taken together, the cumulative evidence is strong that, despite the low volatile content of returned samples, natural gases of internal origin are still being emitted from the moon. This would appear inconsistent with several other lines of evidence, however. The seismometer results indicate a low level of seismic activity (Latham, et al., 1971), and the various lunar magnetism investigations (Dyal, et al., 1971) indicate low internal temperatures. Also, the large positive gravity anomalies ("mascons") discovered by Muller and Sjogren (1968) over circular maria indicate high strength for the interior; Kaula (1969) has concluded that, since mantle convection appears ruled out by the geologic evidence, the mascons must be supported by elastic strength, implying that the moon is rigid to at least 160 kilometers depth. This is in accord with pre-Apollo theoretical studies indicating that present magma generation in the moon would be confined to depths below 500 km (Lowman, 1963; Fricker, et al., 1967).

It is therefore concluded that the moon is geologically active, but only at great depths, and that landscape evolution from internal causes is largely complete.

SUMMARY

The most important aspect of the moon's geologic evolution is that most of it took place before the formation of the oldest known rocks on earth; the moon is indeed a primitive planet, on which the very earliest stages of crustal evolution are preserved. The actual origin of the moon is still very much a mystery, although new geologic discoveries since the beginning of manned exploration are leading to rapid progress in its solution. Of particular importance is the clear evidence that the moon's origin, at least in the later stages, was a high temperature process, causing loss of volatiles. This loss can be considered a primordial, pre-accretion differentiation process — a Stage 0 in terms of the outline presented here.

Two major periods of planetary differentiation can be identified in the moon's geologic evolution. The first of these produced a moon-wide crust several kilometers thick, most of which survives as the lunar highlands (outside the mare ejecta blankets). This crust appears to resemble high-aluminum basalt or gabbro in regional composition, with local areas of high-calcium anorthosite and related rocks produced by magmatic differentiation. The magmas which formed this crust were probably generated by partial melting of the outer few hundred kilometers of the moon during the moon's origin and in the first billion years of its history. A second period of magma generation — the second differentiation — produced the iron-rich magmas which, in many eruptions, formed the maria. From a geochemical viewpoint, this was essentially the completion of the moon's evolution, except for minor post-mare vulcanism and the relatively feeble loss of gas from the deep interior still occurring today. Landscape evolution continued, however, as a result of cratering by objects from outside the earth-moon system, so that the present physiography is a complex mixture of impact and igneous features.

It is hardly necessary to point out that this paper has necessarily stressed areas of agreement among scientists rather than areas of disagreement. Problems that are still acute include the composition and origin of the highland crust; the reasons for the assymetric distribution of maria; the role of vulcanism in formation of ray craters; the relation between lunar and terrestrial anorthosites; and the nature of the lunar interior. The major unsolved problem is of course that of the moon's origin, and its relation to the earth. To use Firsoff's (1962) phrase, is it "Earth's fair child, or a foundling?" Or something else altogether?

ACKNOWLEDGEMENTS

This paper is the outgrowth of a course in lunar geology that I taught at the University of California (Santa Barbara) in the winter of 1970; it owes much to stimulating discussions with students and faculty of the Department of Geology. I am also indebted to my colleagues at Goddard Space Flight Center for discussions, information, and reviews: B. M. French, N. M. Short, C. C. Schnetzler, J. A. Philpotts, L. S. Walter, J. A. O'Keefe, H. W. Blodget, J. Gerard, J. Trombka, B. M. Lowrey, W. S. Cameron, and D. A. Beattie (NASA Headquarters). Dr. Isidore Adler kindly permitted the use of preliminary data, including Figure 7, from the S-161 experiment on Apollo 15.

The U.S. Geological Survey's Astrogeology Branch has provided many maps and open-file reports that have been invaluable in preparing this paper.

The Apollo and Lunar Orbiter photographs presented were supplied by the National Space Science Data Center, Goddard Space Flight Center.

I wish to thank Drs. P. N. Fenner and P. J. Wyllie for their encouragement in, respectively, starting and finishing the paper.

Finally, I thank my wife, Karen, for her interest and encouragement in this work.

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Figure 1. Oblique view to west of Apollo 11 landing site (arrow), taken from LM Eagle at about 95 km altitude. Hypatia Rille at top center. Low sun angle accentuates ridges in Mare Tranquillitatis. Highlands (terrae) at left are about 50 km from Apollo 11 site, hence may be the source of exotic fragments in soil ("anorthosite," KREEP). Large crater at lower right is Maskelyne. NASA Photograph AS 11-37-5437.

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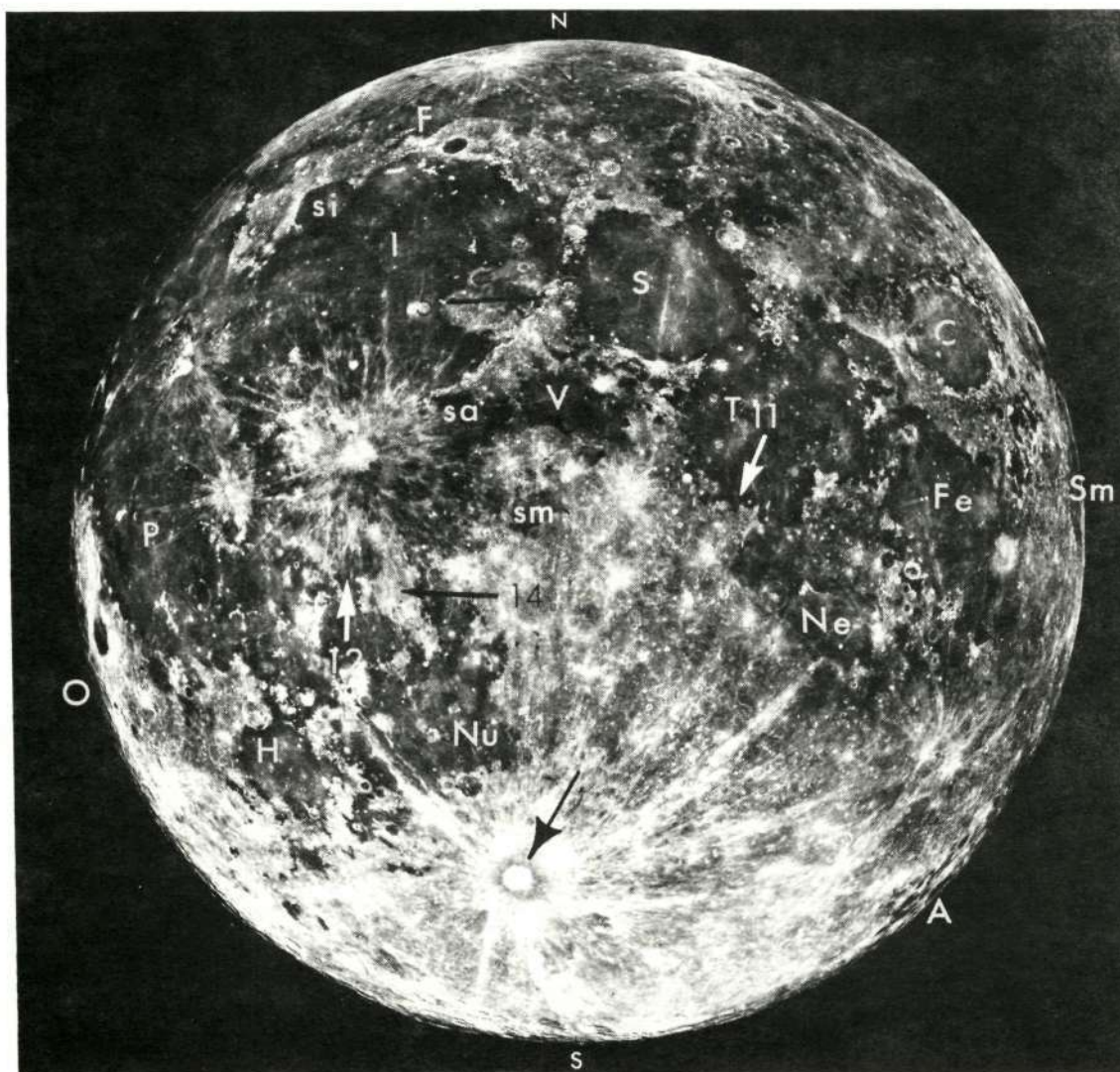


Figure 2. Full moon photograph by Moore and Chappel, 36-inch Lick Observatory refractor, made Jan. 17, 1946. High sun angle emphasizes albedo differences and distribution of maria. Major landmarks labeled as follows:

O - Mare Orientale
P - Oceanus Procellarum
I - Mare Imbrium
S - Mare Serenitatis
T - Mare Tranquillitatis
N - Mare Nectaris
F - Mare Fecunditatis
C - Mare Crisium
Sm - Mare Smythii
A - Mare Australe

Apollo landing sites: 11, 12, 14, and 15 shown with arrow and circle.
si - Sinus Iridum
pl - Plato
a - Archimedes
c - Copernicus
pt - Ptolemaeus
t - Tycho; Surveyor 7 landing site to north with triangle
16 - Descarte area; Apollo 16 landing site.

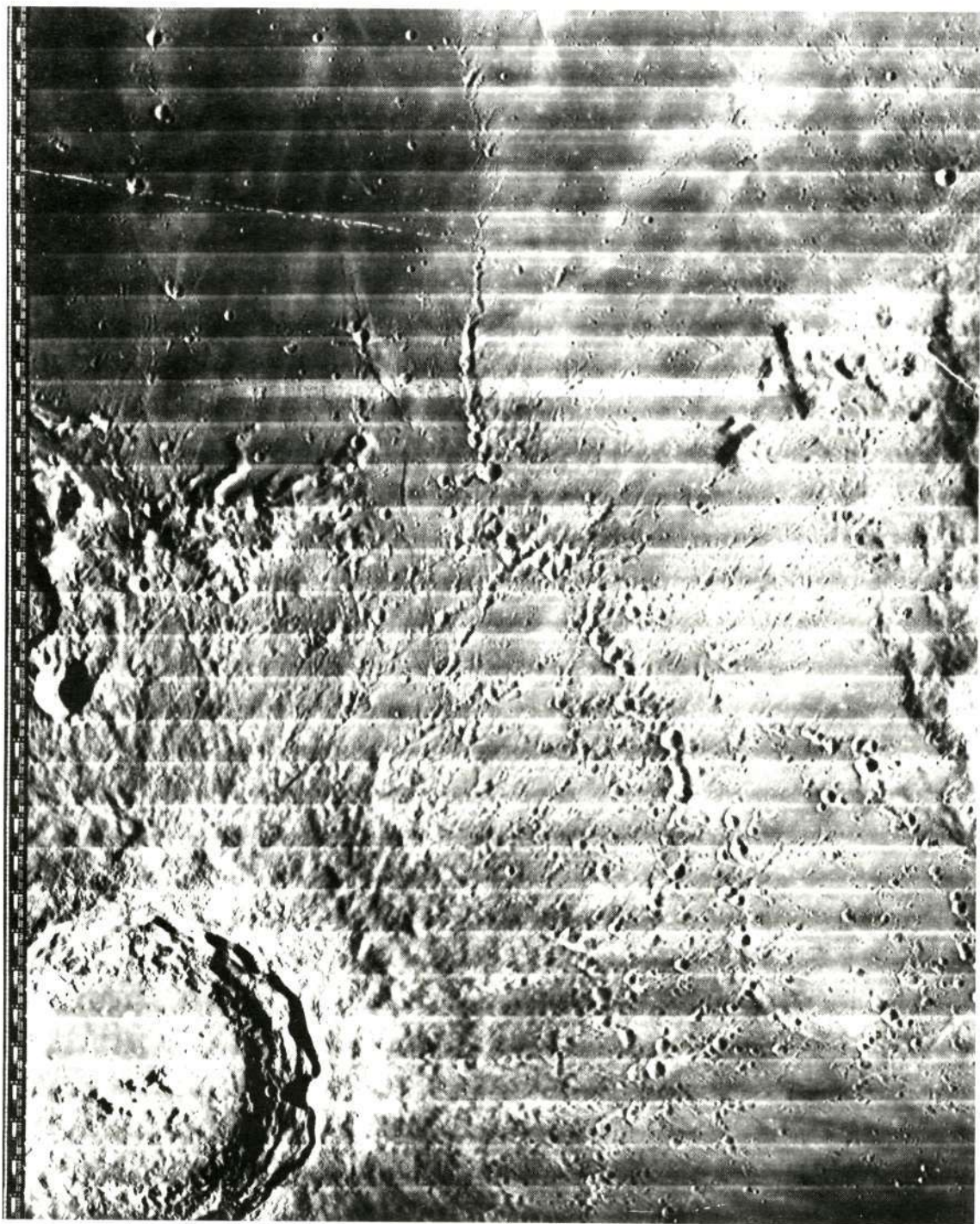


Figure 3. Lunar Orbiter IV photograph, showing area about 200 by 280 km, with crater Copernicus at lower left. Streak at top center is processing defect. Note secondary craters, grading into rays. Some simulate chain craters. NASA Photograph, Lunar Orbiter IV-121H₂.

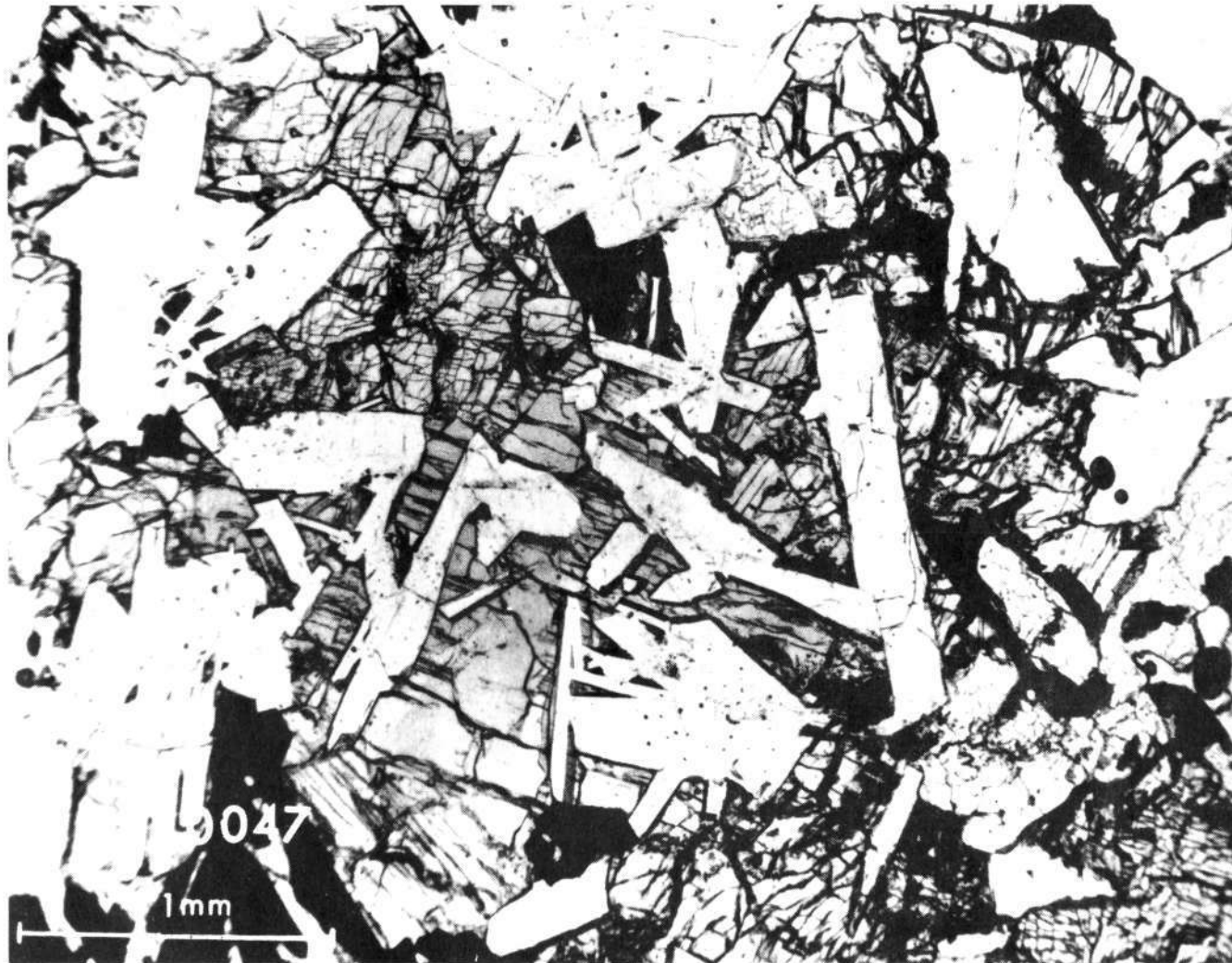


Figure 4. Photomicrograph of Apollo 11 sample 10047, showing typical basalt. Light gray crystals plagioclase, dark gray clinopyroxene, opaques chiefly ilmenite. Note absence of intense fracturing and hydrothermal alteration. NASA Photograph 70 - H - 227.



Figure 5. Photomicrograph of Apollo 12 breccia sample 12057, 11. Breccia consists of rock and mineral fragments and glass spherules in fine-grained opaque matrix. Probably formed by shock lithification of soil by repeated impacts that formed the regolith and small mare craters (e.g., Short, 1970).

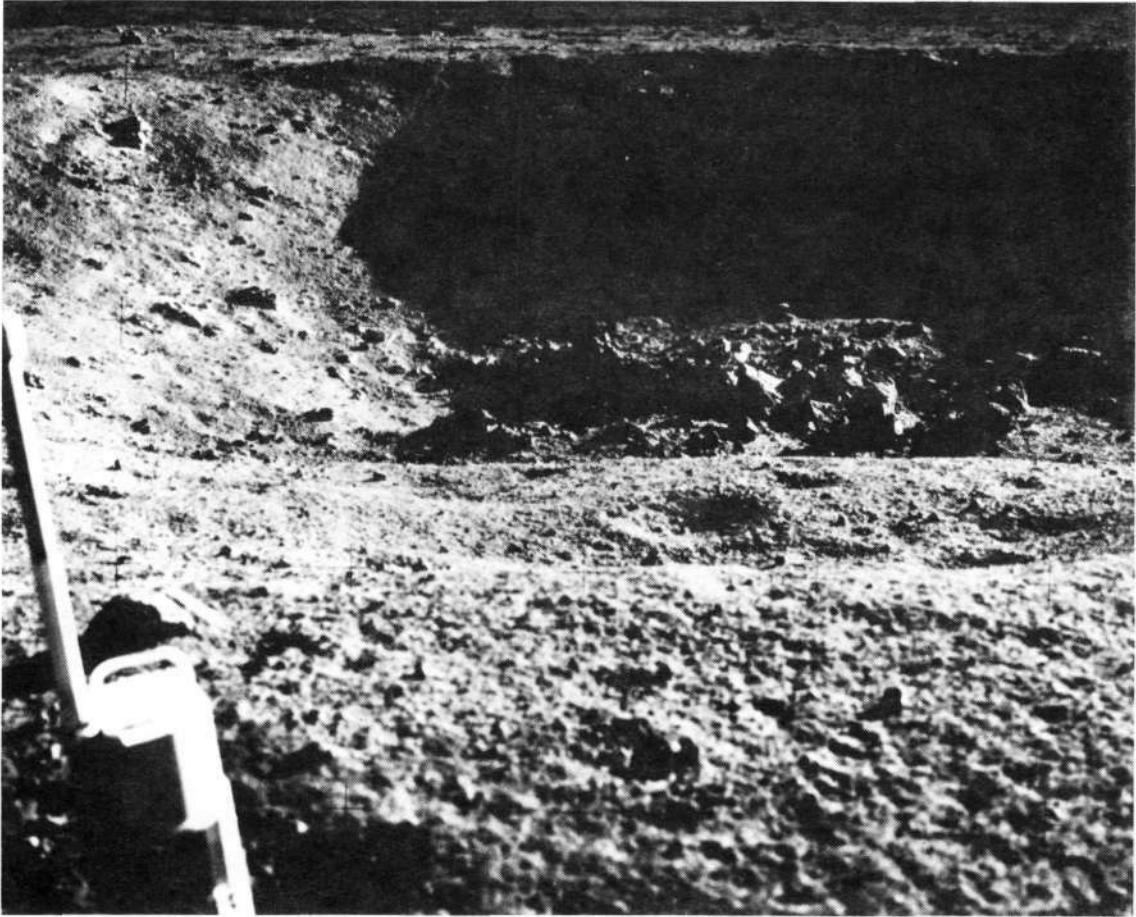


Figure 6. EVA photograph from Apollo 11 mission taken by N. A. Armstrong (Aldrin, et al., 1969), showing crater about 54 meters east of LM. Crater is 33 meters wide and 4 meters deep, probably exposing bedrock at bottom of crater. Lunar surface close-up camera at lower left.

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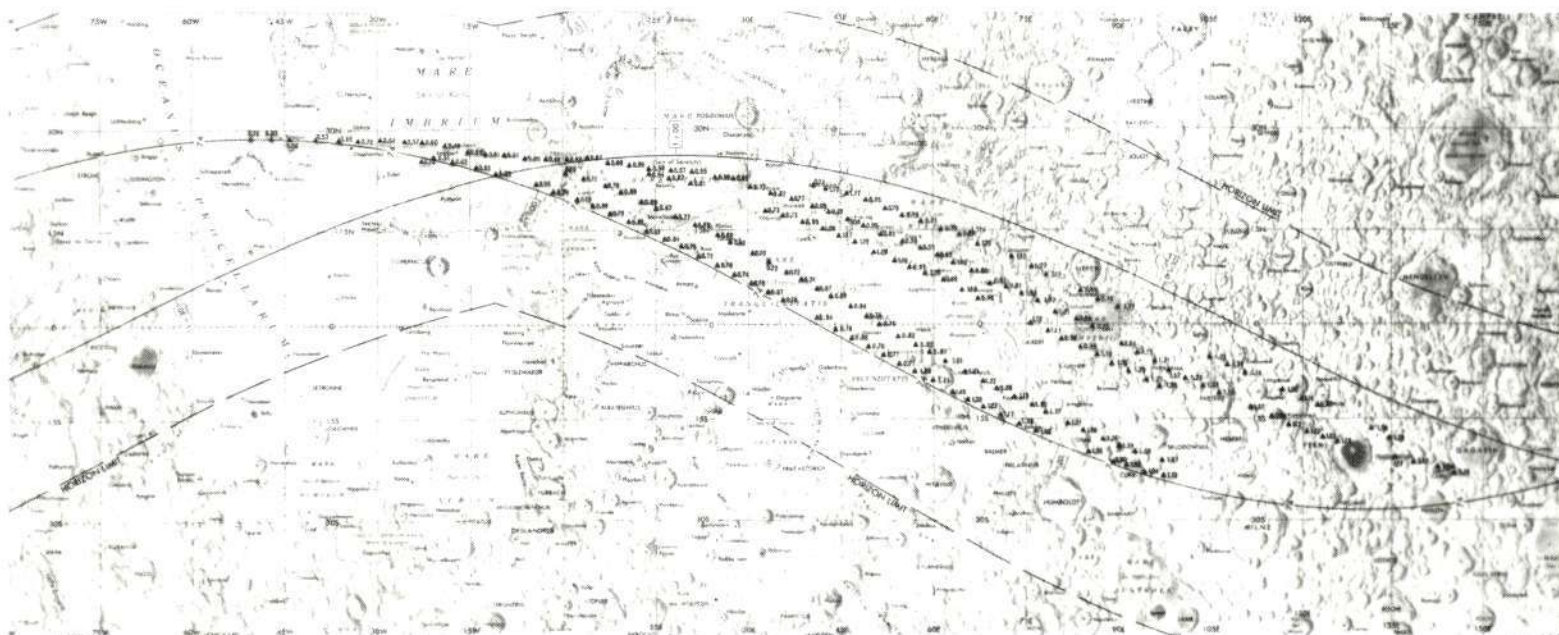


Figure 7. Aluminum/silicon fluorescent X-ray intensity ratios, from Apollo 15 S-161 experiment (Adler, et al., 1971). Based on preliminary calculations for selected ground tracks. Note high aluminum content over highlands at right.

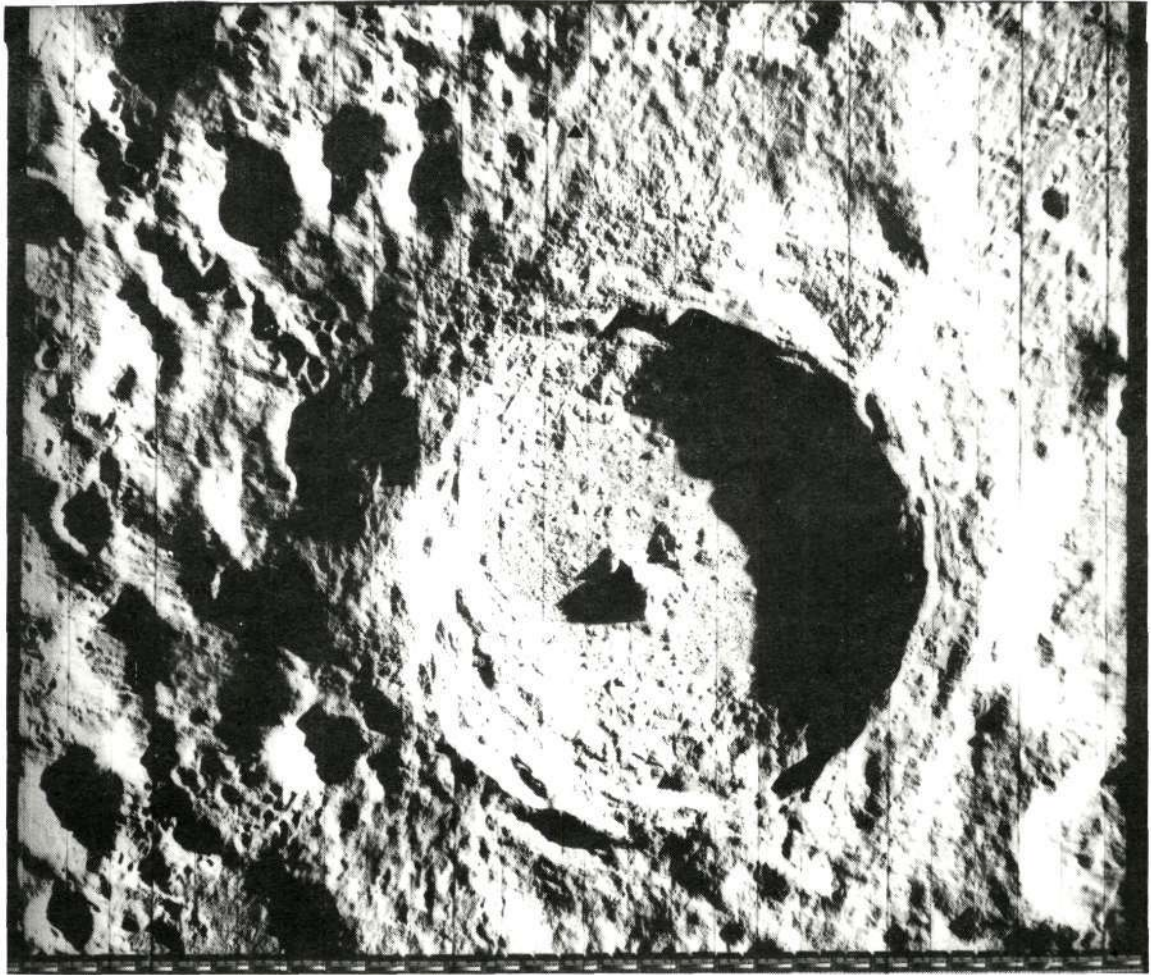


Figure 8. Lunar Orbiter V photograph, showing crater Tycho (85 km diameter). Surveyor 7 landing site north of crater marked with circle and "S". Rough floor of crater thought to be impact melt or post-impact volcanics. Note smooth "playas" on east rim of crater at right; crater counts suggest these to be internally-generated volcanics. Tycho is one of the youngest large craters. NASA Photograph Lunar Orbiter V-125M.

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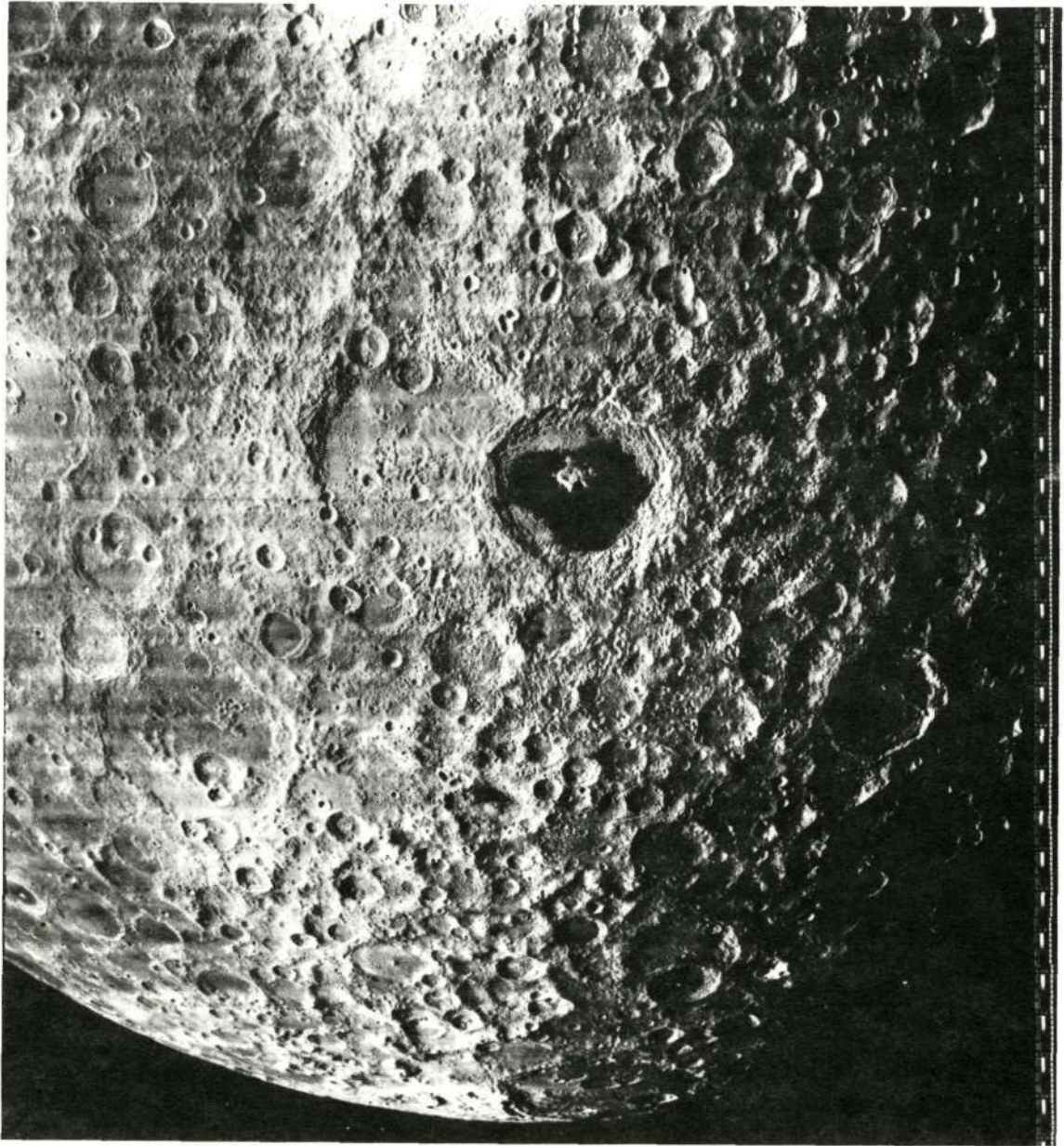


Figure 9. Lunar Orbiter III photograph, north at top, showing far side and crater Tsiolkovsky (240 km diameter). Note both impact melt? and mare material on floor. Freshness of topography, but lack of rays, suggests Eratosthenian age. NASA Photograph Lunar Orbiter III-121M.

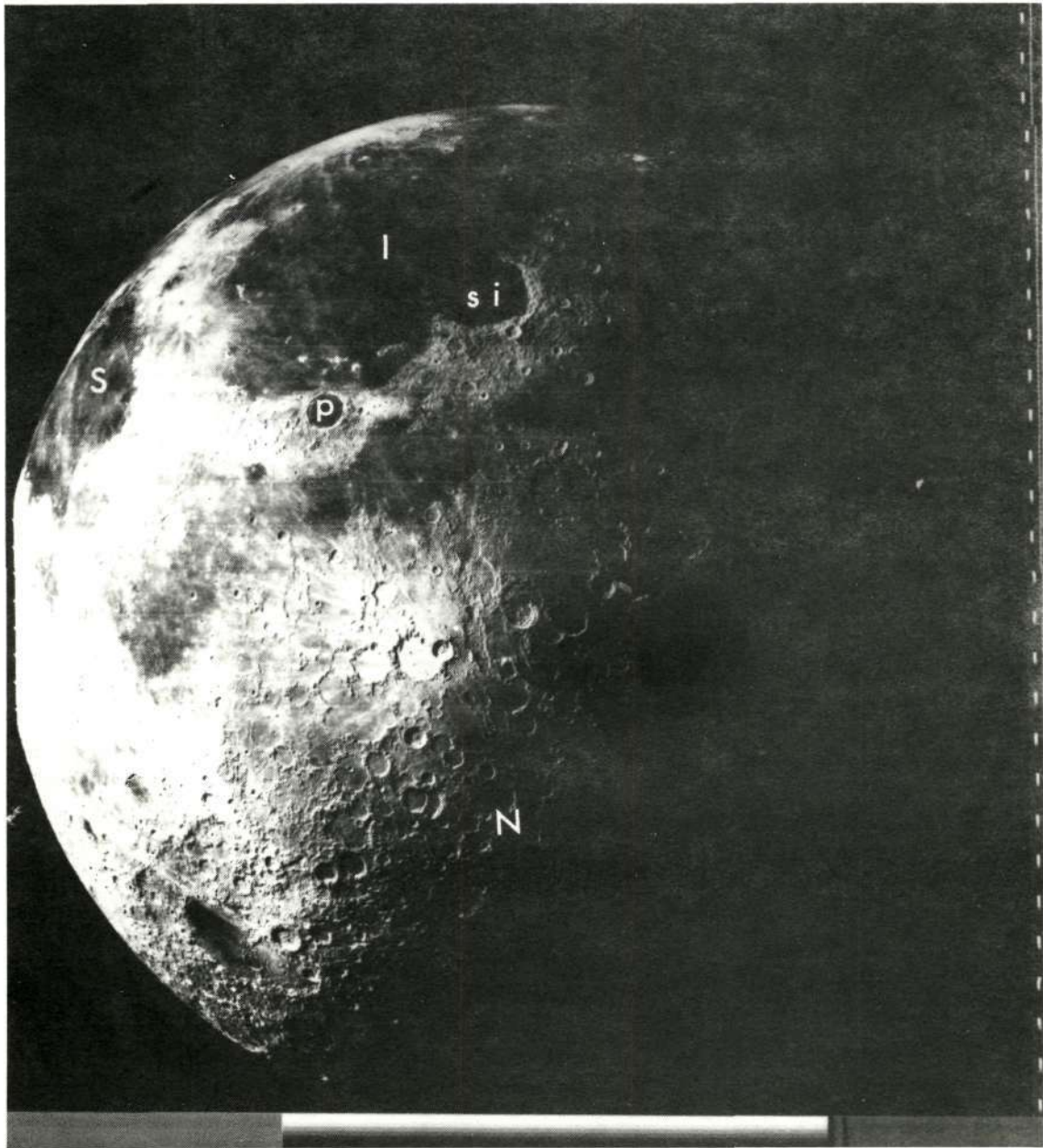


Figure 10. Lunar Orbiter IV photograph, showing north pole of moon (N) from 3400 km altitude. Arrow points to earth. Landmarks identified thus: Mare Imbrium - I; Mare Serenitatis - S; Archimedes - a; Plato - p; Sinus Iridum - si. Post-basin, pre-mare craters well-shown.

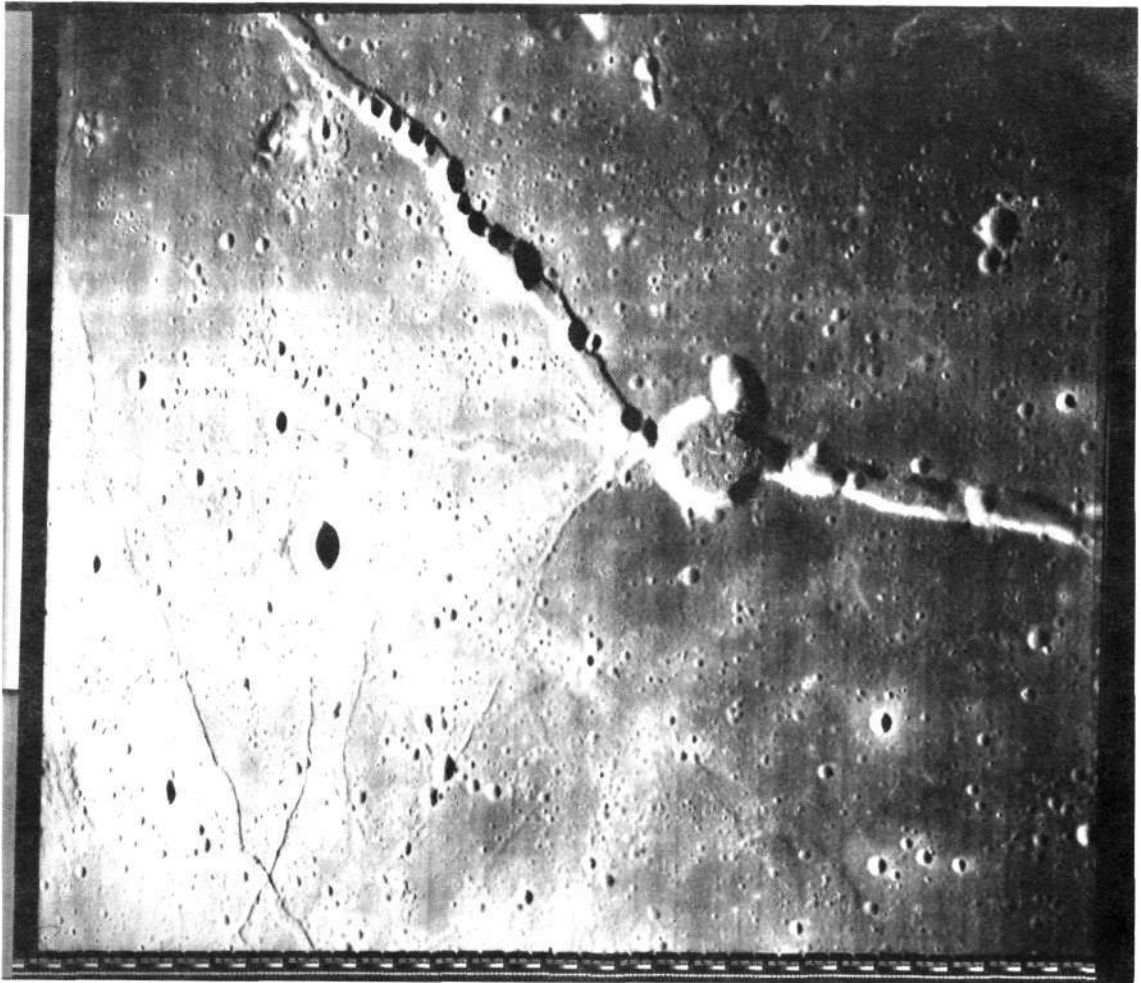


Figure 11. Lunar Orbiter V photograph, north at top, showing Hyginus Rille, named after crater Hyginus (6.5 km diameter) at center. Note gradation into probable grabens at left. NASA Photograph, Lunar Orbiter V-95M.

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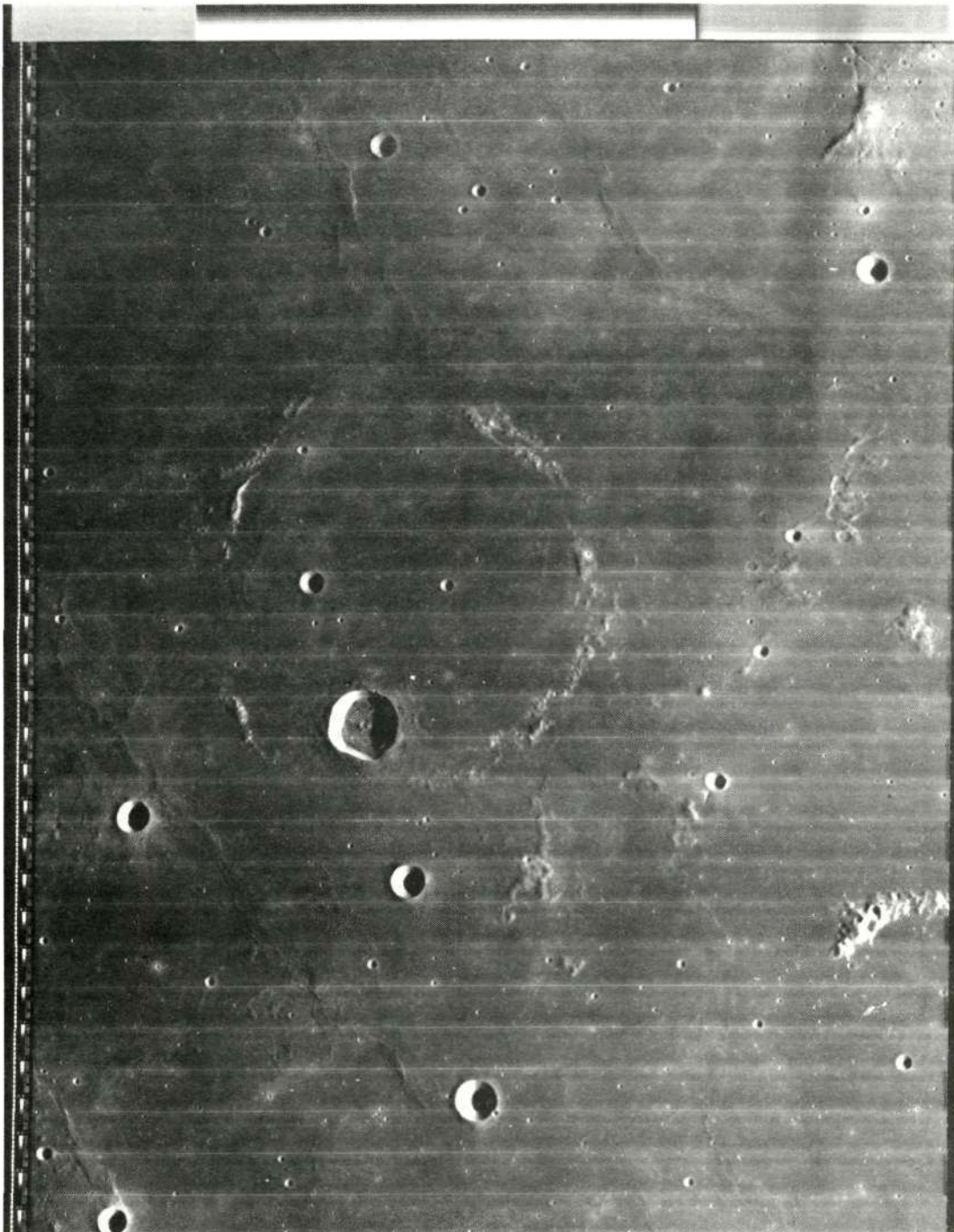


Figure 12. Lunar Orbiter IV-photograph showing Flamsteed Ring, about 100 km wide. North at top. Ring interpreted as flooded, pre-mare crater (Marshall, 1963) and ring of post-mare silicic extrusives (O'Keefe, et al., 1967). Relation to mare ridges suggests extrusion of post-mare silicic differentiates. NASA Photograph, Lunar Orbiter IV-143H₂.

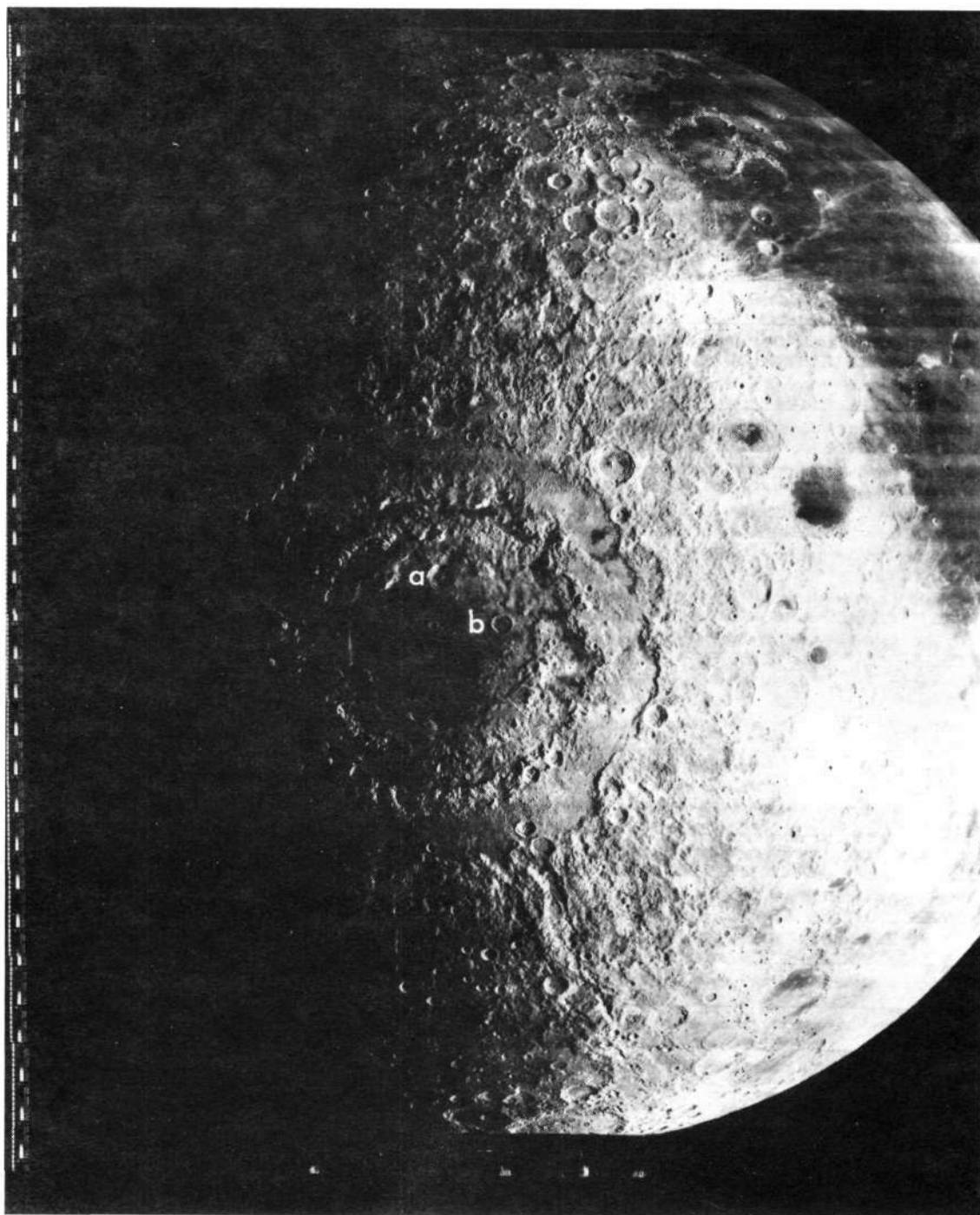


Figure 13. Lunar Orbiter IV photograph showing Orientale Basin, north at top. Outer ring has diameter of about 1000 km. See index photograph (Figure 2) for location. M. Orientale considered type example of fresh impact basin. "a" and "b" refer to following figure. NASA Photograph, Lunar Orbiter IV-187M.

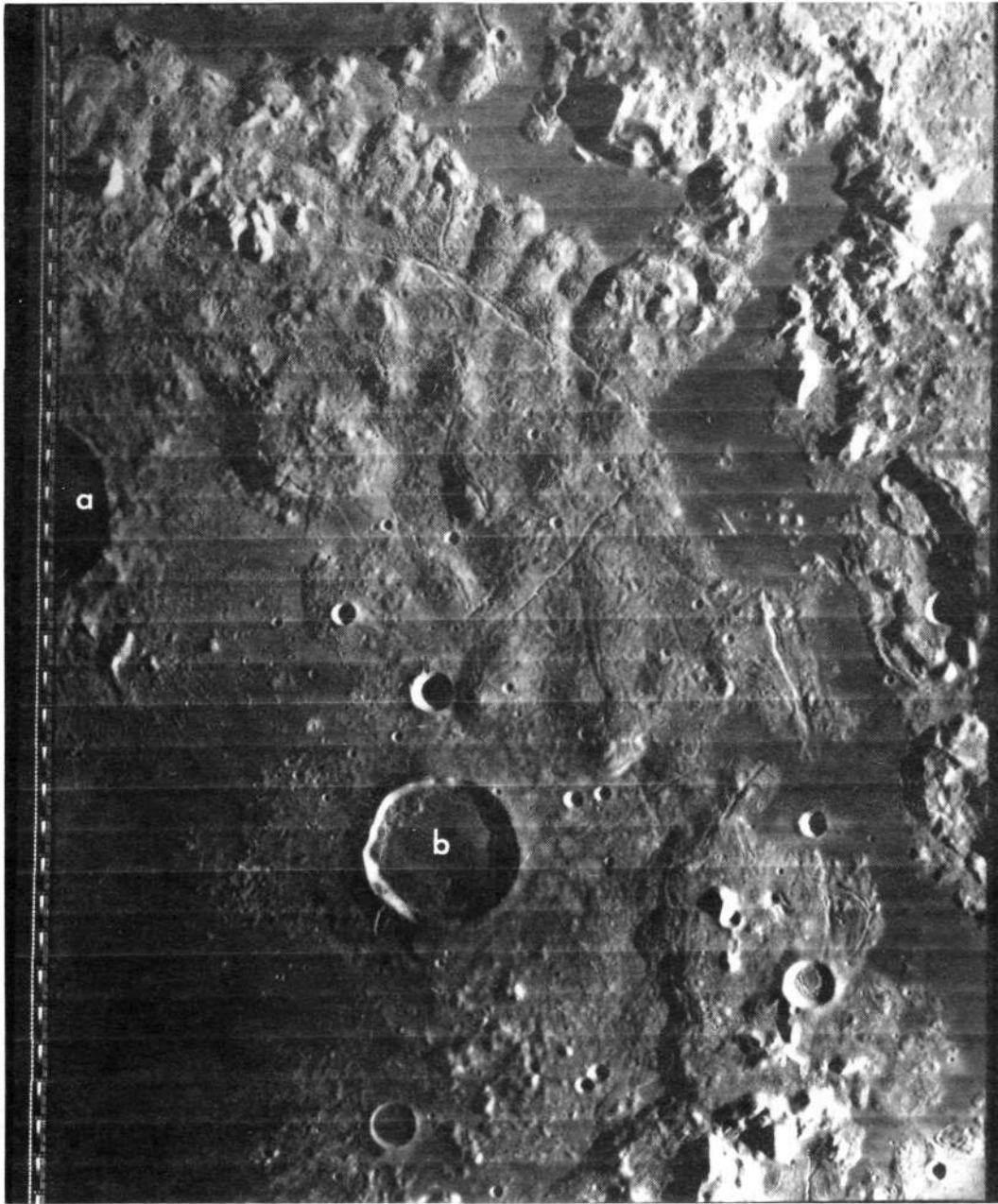


Figure 14. Lunar Orbiter IV photograph showing inner part of Orientale Basin, north at top. Crater "a" considered impact by McCauley (1967), from similarity to Copernicus except for size (55 km diameter). Crater "b" (diameter 35 km) considered volcanic from absence of secondary craters, central peak, and hummocky ejecta. Note that both a and b are post-Orientale Basin, so differences can not be attributed to age. Note low crater density in mare compared to adjacent terra, showing time gap between basin formation and mare eruptions (Gault, 1970).

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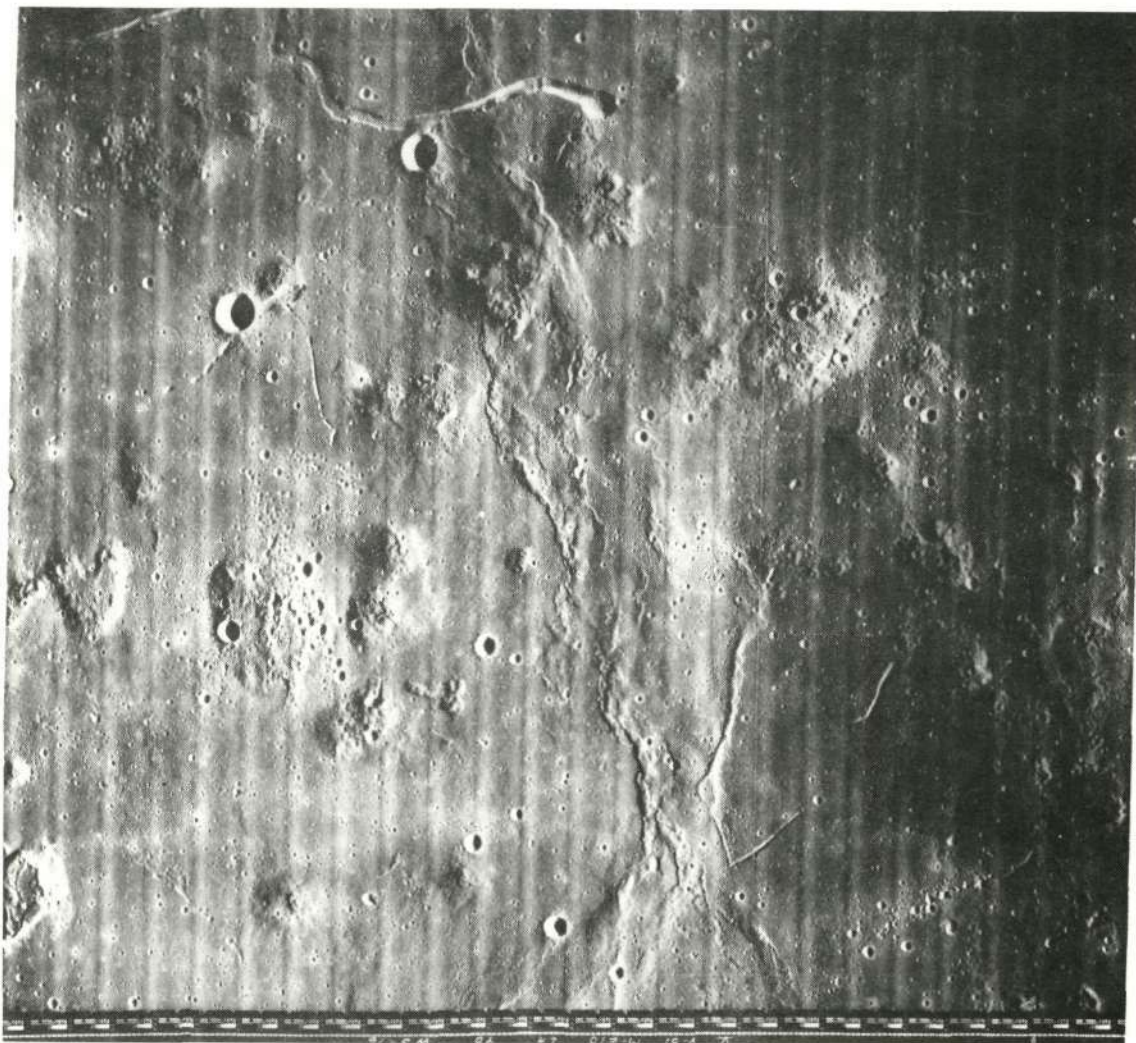


Figure 15. Lunar Orbiter Photograph showing Marius Hills; north at top. Area covered measures about 94 by 77 km. Domes considered to be volcanoes. Note sinuous rilles cutting across mare ridges, indicating internal origin rather than surficial erosion. NASA Photograph, Lunar Orbiter V-213M.

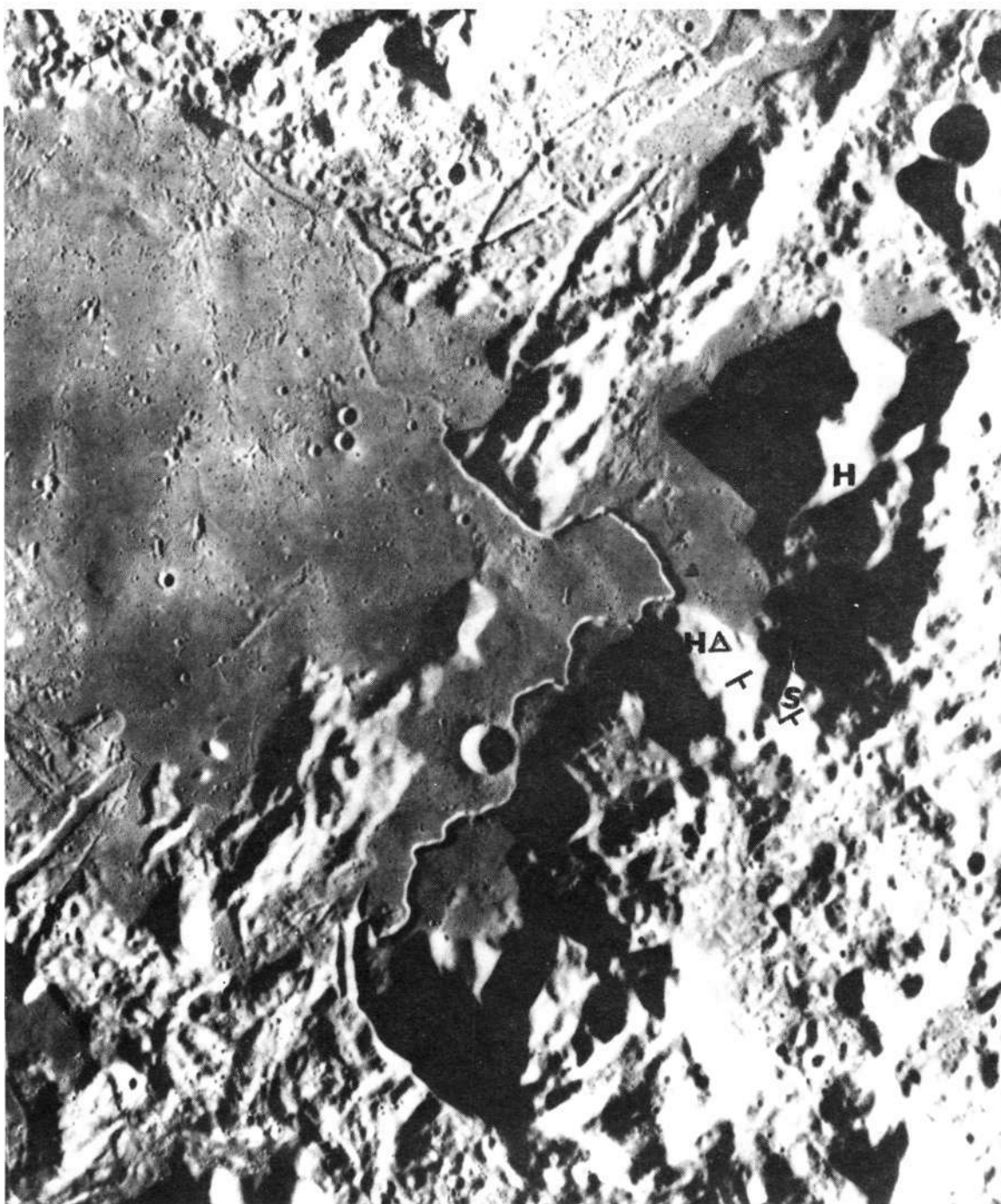
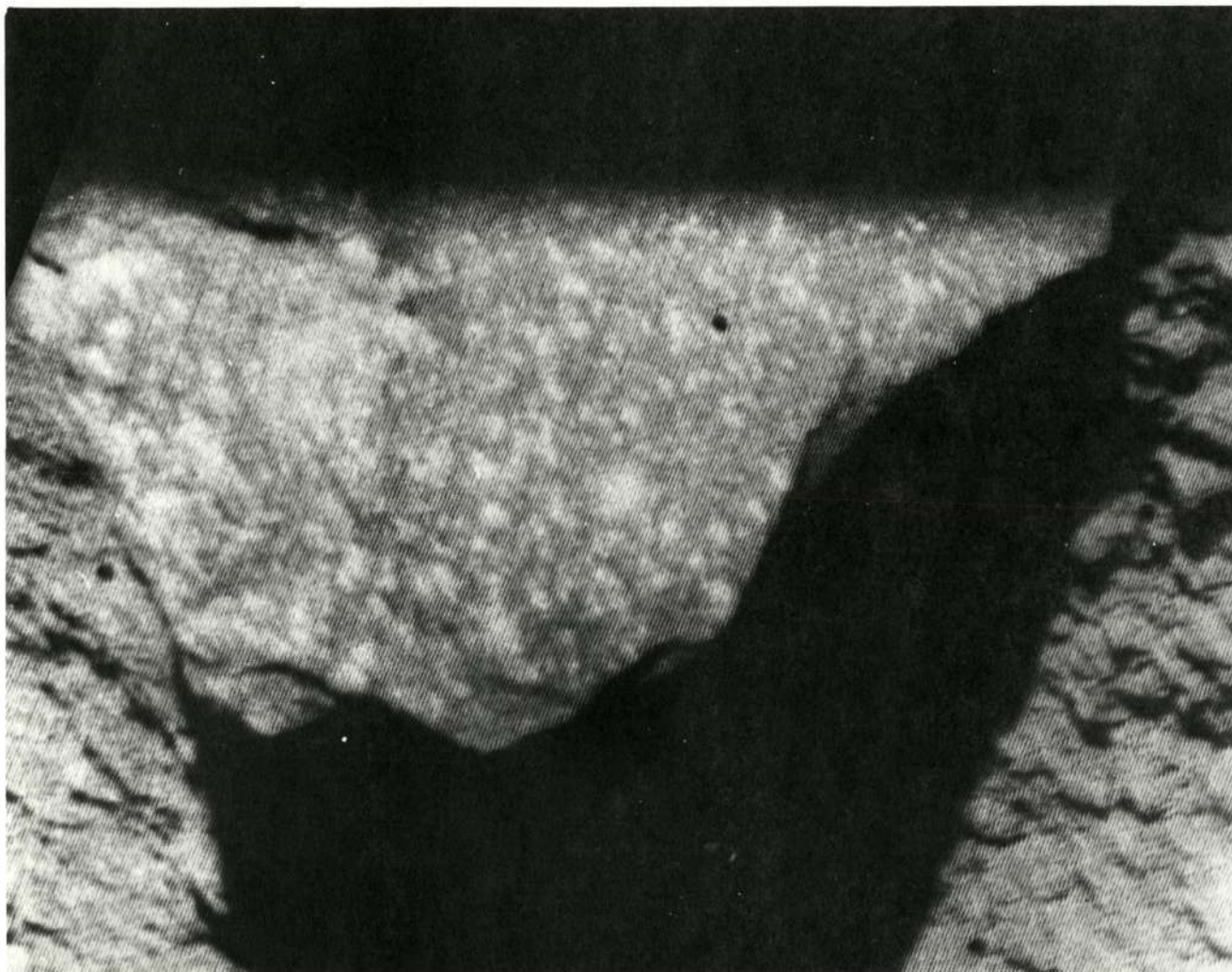


Figure 16. Apollo 15 metric camera photograph, showing LM landing site (triangle) east of Hadley Rille; north at top. Distance from Mount Hadley (H) to Hadley Delta (H triangle) about 30 km. Palus Putredinus (PP) is mare area. Dip of strata in Hadley Delta and Silver Spur (S) shown diagrammatically. NASA photograph 71-H-1441 or AS 15-M3-1677.



Figure 17. Apollo 15 surface photograph; view to northwest along Hadley Rille. Note horizontal or nearly horizontal attitude of strata in walls. Rille is incised in mare lavas of Palus Putredinus. D. R. Scott by rover. NASA Photograph 71-H-1426.



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Figure 18. Surveyor VII television photograph showing rock about 25 cm long with possible phenocrysts. Chemical composition suggests phenocrysts may be plagioclase (Patterson, et al., 1970; Jackson and Wilshire, 1968). NASA Photograph, Surveyor VII, W-54.

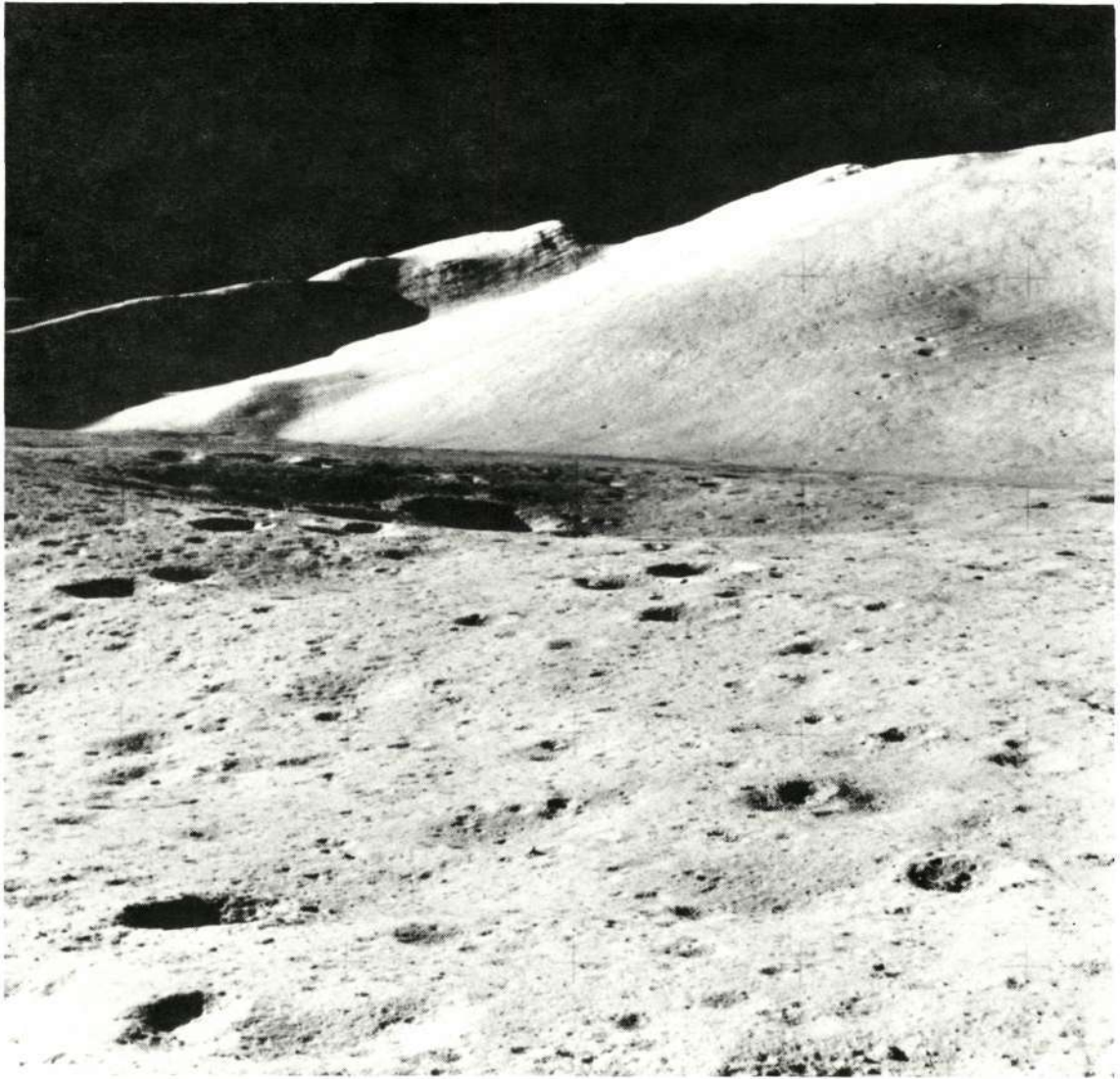


Figure 19. Apollo 15 surface photograph; view to southeast toward Silver Spur, with Hadley Delta at right. Note parallel planar structures in both Silver Spur and Hadley Delta; dip is away from Imbrium Basin (Figure 16). NASA Photograph AS 15-87-11748.

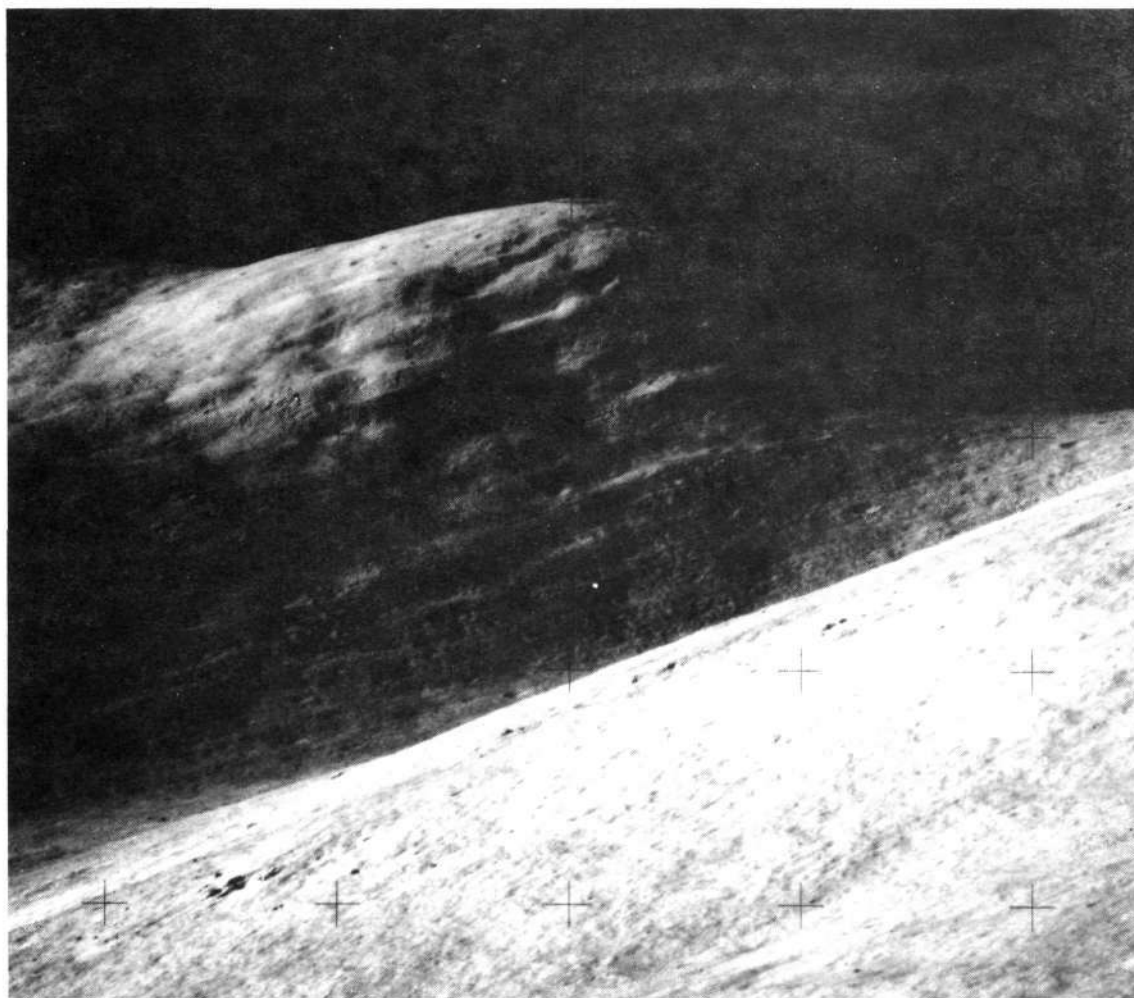


Figure 20. Apollo 15 surface photograph with 500 mm telephoto lens, showing close-up view of Silver Spur, about 800 meters high. Planar structures interpreted here as layered volcanics of pre-mare crust; Carr and El-Baz (1971) map this as massif materials of Imbrium Basin, and interpret it as mare basin ejecta from pre-Imbrian basins (pre-Apollo 15 interpretation).

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Figure 21. Apollo 15 surface photograph; view to north, showing Mount Hadley, about 4400 meters high. Planar structures resemble those in Hadley Delta; if the same, dip is opposite (toward Imbrium Basin). NASA Photograph AS 15-87-11849.

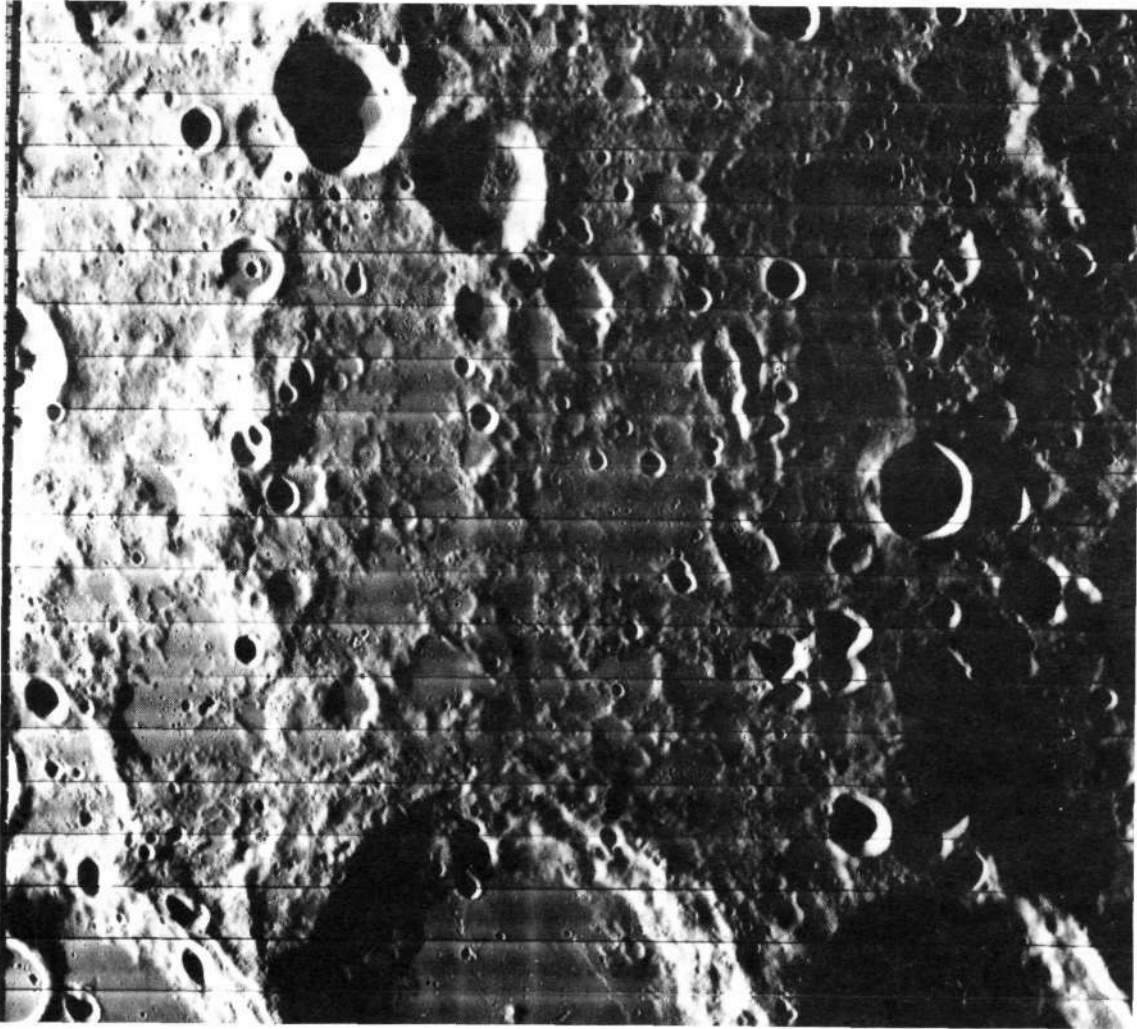


Figure 22. Lunar Orbiter V photograph showing portion of far side highland terrain with relatively smooth intercrater areas, similar to those of the near side southern highlands interpreted as crust formed by first differentiation before intense bombardment began. NASA Photograph 67-H-1099.

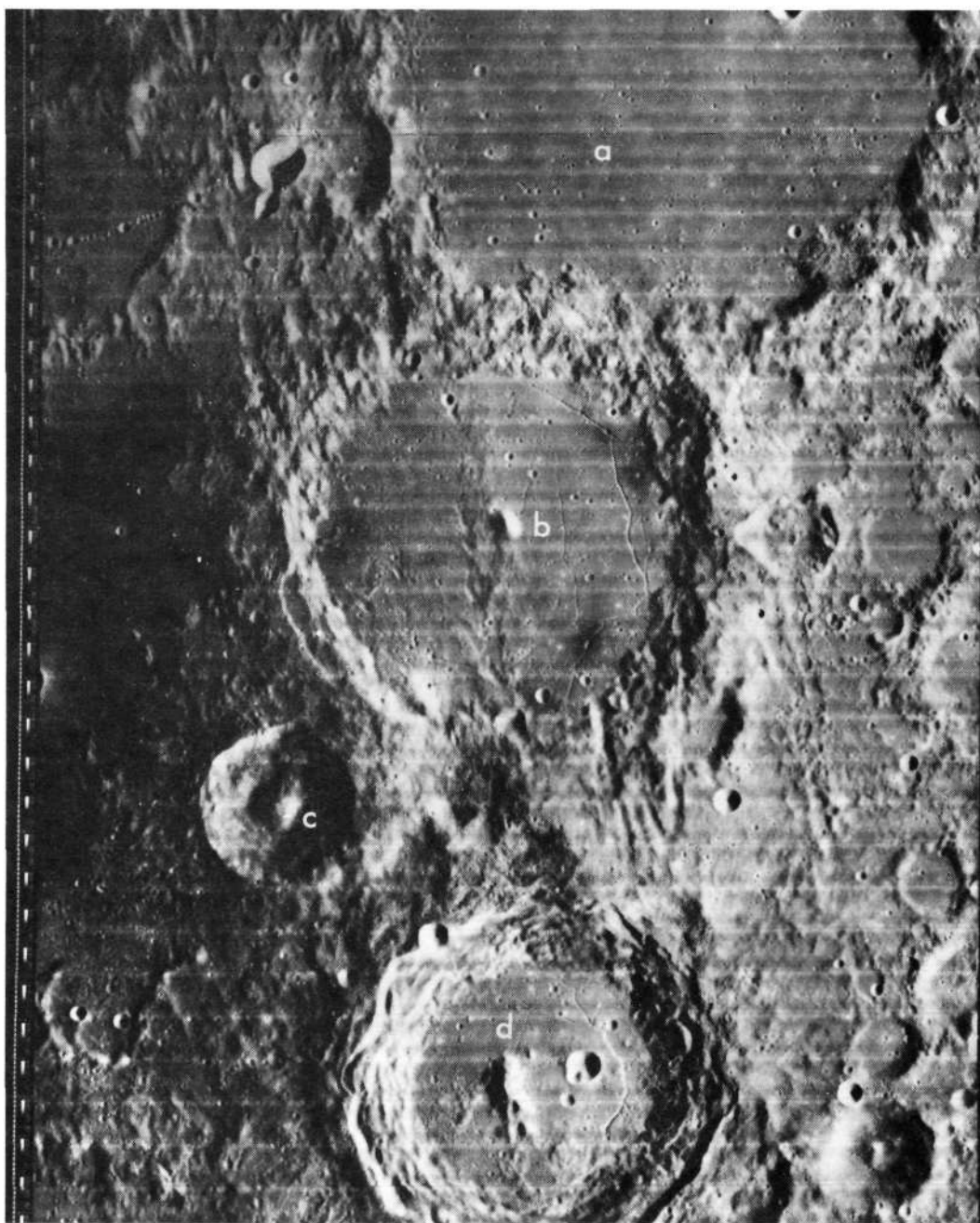


Figure 23. Lunar Orbiter IV photograph showing craters Ptolemaeus (P), Alphonsus (Al), Alpetragius (Ap), and Arzachel (Ar). Ptolemaeus and Alphonsus floored chiefly with Cayley formation (Howard and Masursky, 1968), mare-like material between Fra Mauro formation and mare lavas (left) in age. Note dark-halo craters in Alphonsus, interpreted by Howard and Masursky as Copernican maars. Central peak of Alphonsus is site of transient event and spectrograms reported by N. A. Kozyrev in 1958.

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Figure 24. Apollo 15 surface photograph; view to west across Hadley Rille, showing layering of multiple flows or sills in Palus Putredinus basalts. Thinest layers are several meters thick. Regularity of layers suggests low cratering rate at time mare was formed. NASA Photograph 71-H-1427.

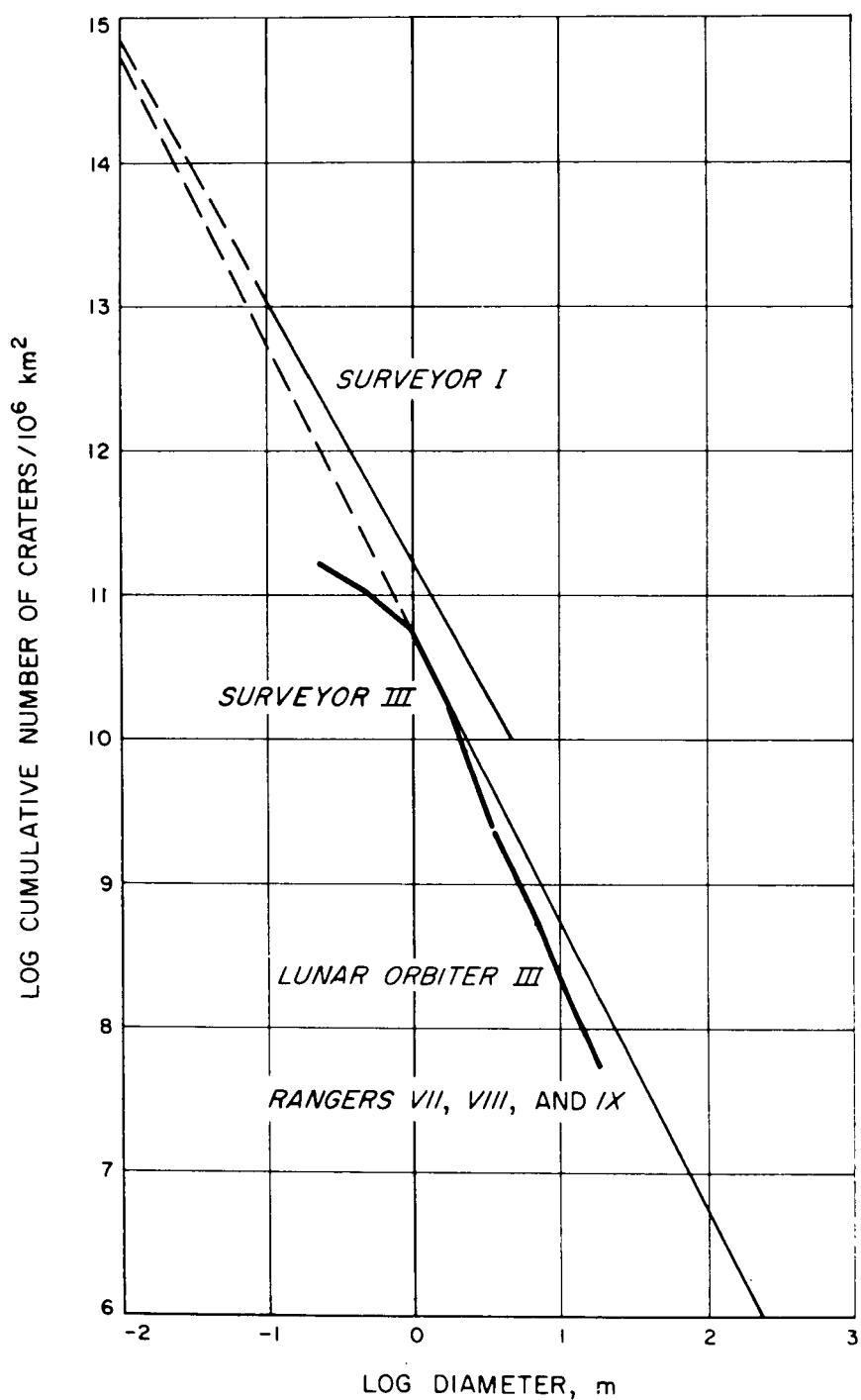


Figure 25. Size-frequency log-log plot of small craters from Ranger, Lunar Orbiter, and Surveyor spacecraft photographs (Shoemaker, et al., 1967) showing overlap in distribution of crater sizes in the 100 meter - 0.1 meter size.

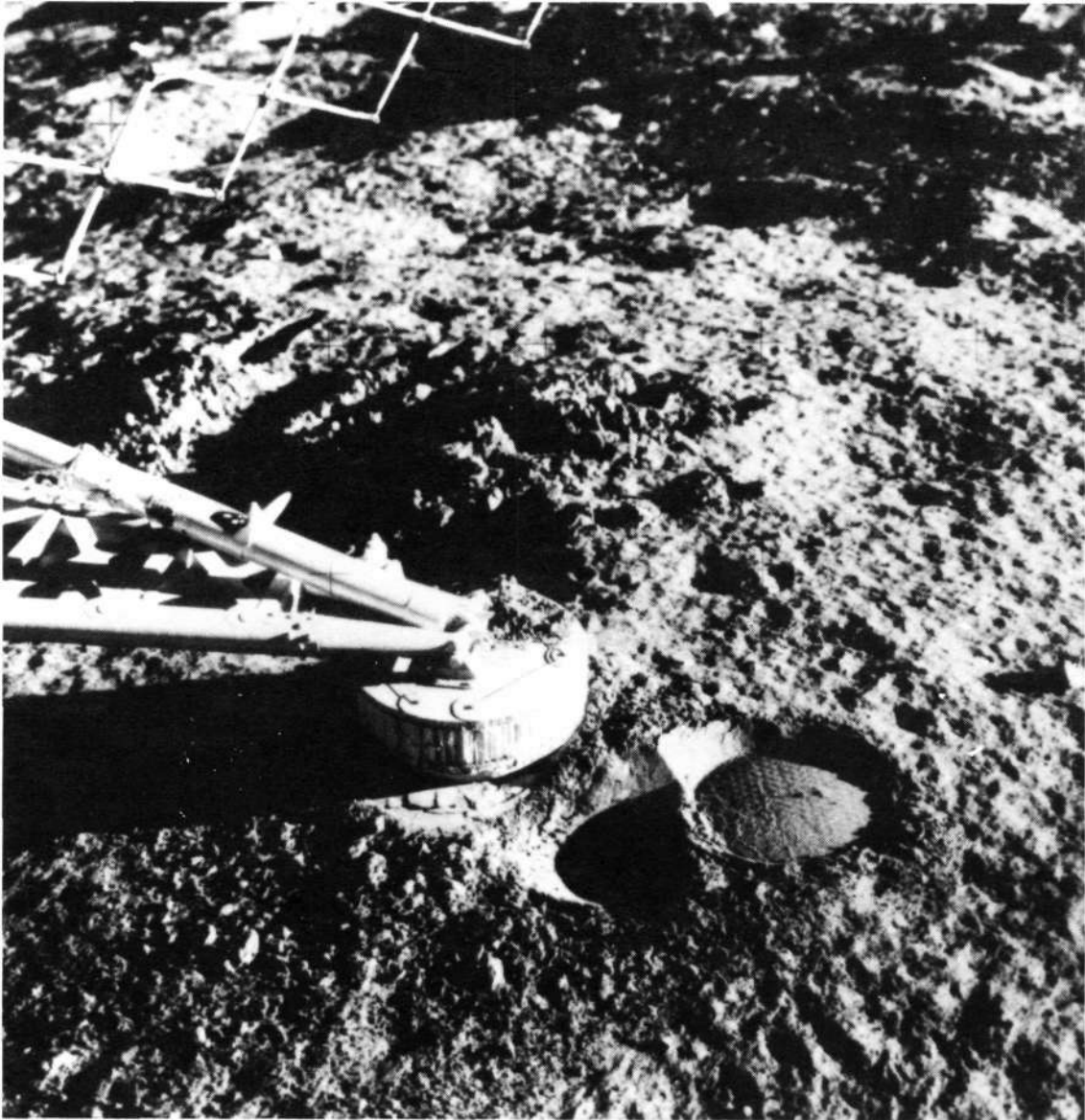


Figure 26. Apollo 12 surface photograph taken by astronauts during re-visit to Surveyor III, before spacecraft was disturbed. This is the original footprint made by Surveyor on landing 2 1/2 years earlier. Extreme freshness demonstrates low micrometeorite flux and rate of mass wasting and freedom from major seismic activity during this period. NASA Photograph AS 12-48-7110.